ISSN 1173-5996

Full-Scale Compartment Fire Experiments on "Upholstered Furniture"

by

Nabil Girgis

Supervised by
Dr Charley Fleischmann

Fire Engineering Research Report 00/5
March 2000

This report was presented as a project report as part of the M.E. (Fire) degree at the University of Canterbury

School of Engineering
University of Canterbury
Private Bag 4800
Christchurch, New Zealand

Phone 643 364-2250
Fax 643 364-2758
www.civil.canterbury.ac.nz

Abstract

This experimental research is part of an overall ongoing research program on domestic fire hazards, conducted at the University of Canterbury, Christchurch, New Zealand, by the Civil Engineering Department (Fire Engineering).

The research program aimed to predict the behaviour of upholstered furniture in fires and the hazards produced during their burning. Experiments were conducted on six identical style chairs inside the standard ISO-Room. The six chairs had the same size, shape, timber frame, and fabric, but a different type of foam was used for each chair. Experimental measurements for each chair included: Heat-release rate, heat-flux on the floor of the fire-test room, mass-loss of the burning chairs, and temperature history inside the fire-test room, also the mole fractions of carbon monoxide, carbon dioxide and oxygen inside the exhaust duct. Data is presented in graphs and tables. From the experiments it was found that each type of foam presented different fire hazards. But each of them had a rapid-fire growth. It was also found that some of the chairs produced more than one type of fire hazards and others relatively had a better performance.

Data obtained from ISO Room experiments were compared with those obtained from the furniture calorimeter tests for identical chairs. Studies and analysis carried out and focused on the fire performance for different foam types and the impact of the surrounding environment on the fire hazards produced by each foam type. It was clear from the comparison between both the ISO Room experiments and the Furniture Calorimeter tests that the larger space produced less hazardous effects than a small compartment. The foam performance in the large space was better than its performance inside the small room.

Acknowledgement

I value this opportunity to be able to record my sincere gratitude to the persons who have helped me.

Firstly, I am extremely grateful to both Dr. Andrew Buchanan and my Supervisor Dr. Charles Fleischmann for their continued support along the way. Thanks Andy for all your friendly direction, great help, your valuable time and expert advice. You have been a very positive influence on my career. Thanks Charley for your friendly encouragement. Your technical guidance directed my hands in the experiments and challenged my mind in the analysis. You are simply the man behind my experiments.

I am also grateful to Dr. Allan Tucker from the Mechanical Engineering Department for his contribution to the Fire Engineering Masters Program and for helping me at the early stages of my degree. Thank you Dr. Tucker.

I would like to thank the entire staff of the Engineering Library for their friendly assistance; in particular Pat and Christine. Thanks also to Louise, Catherine, Pat, and Denise from the Civil Engineering Office.

Finally, thanks to my wife and my two lovely sons for their understanding.

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Chapter 1
Introduction

Saving lives is the main concern and objective of fire engineering. Smoke and toxic gases produced from modern synthetic materials used in upholstered furniture and bedding have been recognised as the major causes of death and incapacitation in domestic fires.

Domestic fires as well as most other types of fire occur when an ignition source is applied to combustible materials. Polyurethane foam is used in the design of most of today's upholstered furniture as a primary cushioning material. As with all other organic material, polyurethane foam products will burn when exposed to an ignition source with sufficient heat. Furthermore, in household furnishing some kind of polyurethane foam is almost always used in combination with other flammable materials such as polyester fibrefill, wood and fabric, which accelerate the fire growth.

However, fire engineers can neither control the type of furniture people prefer to use nor even recommend limited-fuel areas inside domestic dwellings, unlike the influence that is possible in the design of certain public places. Furthermore, although building codes may have some control over building materials, they are not involved in the type of furniture inside the building nor they do have any control over human behaviour and carelessness which may cause fires.

Despite a lack of regulations controlling the use of synthetic products in the furniture upholstery industry, what fire engineers can do is provide people who are working in the industry with as much information as possible about the burning behaviour of different components. Secondly, fire engineers can warn of predicted hazards in the event of fire involving furniture so that the safest possible components are used. Towards this aim, this project examines the behaviour of six polyurethane foams currently used in the furniture upholstery industry, through a series of laboratory controlled experiments.

Further to a comparative analysis of the foam, this project also examines the burning behaviour of each foam type in both a strictly controlled compartment situation (ISO

Room) and the less enclosed situation as would occur in large spaces (Furniture Calorimeter).

In summary then this project poses two research questions:

1. Is one Polyurethane foam any less hazardous than another during fire, and to what extent?

2. Do the behaviour of foams tested in a compartment fire differ from those tested in a large space?

Chapter two, Combustion Behaviour, examines the typical behaviour of upholstered furniture in a fire and looks closely at each component of upholstered furniture separately. It also explores the tenability limits, which form the basis of the comparison between foams and explores briefly previous research (NZCBUF # 1) which was done in New Zealand and which relates directly to this project.

Chapter three, Methodology, begins with historical account of the development of full-scale compartment fire measurements and the background for selecting the ISO Room to run the experiments. This is followed by a detailed description of the experimental set up, instrumentation, and procedure. It also explores the items tested and details of the experiments run.

Chapter four, Results, explores the findings obtained from the experiments, for each chair. Comparing between them, in terms of peak-heat release, temperature, smoke species produced from each chair, and time taken to reach the peak value for each chair, it looks closely at experiment number six as a typical run for the others.

Chapter five, Comparison between ISO Room and Furniture Calorimeter, is an examination of two sets of experiments in order to determine the factors that might exit related to the surrounding environment. These factors will have a bearing on the second research question.

Chapter six, Discussion, discussed the project limitations, and discussed the findings from ISO Room experiments which related to research question number one referring to experiment number six as a typical run. The results are then compared between the

ISO Room and the Furniture Calorimeter discussing variations of fire hazards produced according to the impact of surrounding environment.

Chapter seven, Conclusions, outlines conclusions drawn from the discussion and is followed by chapter eight, which suggests further research.

Chapter 2
Combustion Behaviour

Combustion inside a small-enclosed compartment is a hazardous situation, whether this is either slow smouldering combustion with a low temperature, or flaming combustion when the heat source is strong enough to directly produce flames. Victims in fires experience combustion hazards, which consist mostly of exposure to highly toxic and irritating smoke concentrations, low oxygen level, optical obstructions, radiant heat-fluxes, high air temperature and direct contact with flames. Therefore, the conditions in a fire are likely to be lethal or at the very least, individuals will experience incapacitation. Upholstered furniture contains several components each of which produce different fire hazards. Therefore to predict the tenability limits inside a small compartment involved in an upholstered furniture fire, the hazards produced from each one of these components need to be considered.

2.1 Typical Behaviour of Upholstered Furniture in a Fire

Upholstered furniture behaviour in a fire depends on its component characteristics and the fire hazards produced by each one of these items.

2.1.1 Components of Upholstered Furniture in a Fire

The components of upholstered furniture are frame, foam, fabric and interliner, all of which are considered flammable materials. The possible likely behaviour for each one of these components in a fire, could be as follows:

<u>Fabrics</u>

Fabrics used for upholstered furniture might char or melt when exposed to flame. Charring fabrics are typically natural fabrics such as, cotton or wool. These provide a relative amount of protection to the upholstery foam inside from direct exposure to the flame, which may delay the fire build-up and slow fire growth. On the other hand, melting fabrics such as polyester, polyacrylics, propylene, and nylon melt away exposing the upholstery foam directly to the flame.

Foams

Foam is a lightweight cellular material, resulting from the introduction of gas bubbles into reacting polymer which is an organic substance composed of repeating chemical units built up into large molecules. Polyol is the key chemical in foam formulation which when mixed with diiso-cyanates and other specific ingredients, produces the reaction that causes flexible polyurethane foam to form.

Foam production has been likened to the making of bread. Foam ingredients are mixed; they react and then rise to resemble a loaf of bread. But, unlike bread, flexible foam production is much more controlled. New catalysts and additives are continuously introduced to precisely control cell structure and resulting foam performance.

Density is the measurement of the weight, or mass in specific terms of each cubic meter of volume. Density is one of the most important overall determinants of foam performance. Other determinants such as surface firmness measured at indention force deflection (IFD) could be used to evaluate the foam quality but might not affect the foam performance in fire as density does.

Interliners

The degree of flammability of Interliners affects the fire growth for upholstered furniture. The effective fire barrier type interliner delays the fire build up or might completely stop the fire from growing (Sundstrom)[19].

Furniture Design

Most design parameters such as high or low back have no significant influence on fire growth rate. However it has been found that the presence of arm-rests and chair upholstery reaching to the ground, accelerate the development of fire. (Sundstrom) [19]

Frames

Chairs without a frame may be very hazardous although a metal frame will not contribute to the fire. On the other hand, wood frames contribute directly to the fire at late stages and whereas they may not burn completely, the joints may fail early allowing the peak-heat release rate to occur sooner by exposing more upholstery materials to the flame. Plastic frames are the most hazardous material frames in respect to their performance in fire.

2.2 New Zealand- CBUF

The European Commission sponsored a study of the combustion behaviour of upholstered furniture (EC-CBUF), and a factor-based model "CBUF MODEL I" (Enright and Fleischmann) [6], has been developed to predict full-scale results for the peak heat-release rate, time to peak heat-release rate, total heat-release and untenable conditions produced.

NZCBUF # 1

An examination of the applicability of this model to exemplary New Zealand furniture has been carried out at the University of Canterbury, Christchurch, New Zealand (Enright and Fleischmann). [6] It has been observed that the New Zealand exemplary items present a relatively higher peak heat-release rate and are a higher fire hazard than their European counterparts.

NZCBUF # 2

Previous research in New Zealand recommended that a full-scale room fire facility should be at least equivalent to the apparatus described in the ISO 9750 [5]. This study reported that part of the NZCBUF # 2, full-scale experiments and the furniture calorimeter experiments were conducted along with cone calorimeter tests for New Zealand style upholstered furniture.

2.3 Tenability Limits

It is valuable to highlight the tenability limits for victims in a fire environment when exposed to heat-flux and also to evaluate the toxic effects of inhaled toxic gases produced from burning items. That forms the basis of this study together with a comparison between the different polyurethane foams used in upholstered chairs. Concentration of toxic gases is considered one of the most significant parameters to assess the fire hazards.

In a work environment when the room is on fire, a normal, healthy person should be able to evacuate the room of fire origin or the building in two or three minutes before the conditions become untenable. However, in domestic dwellings the occupants might be asleep or have a disability, which means they may need a longer time to respond and react to the fire indications.

Exposure to Heat-Flux

Victims in fires may die or at least experience incapacitation due to exposure to heat either by heat stroke, body surface burns or respiratory tract burns. (Purser) [15]. Exposure to heat gradually increases the body core temperature. Once the body core temperature reaches 40° C, consciousness becomes blurred. Animal experiments and studies suggest that exposure to the temperature of 120° C for a few minutes is likely to cause death due to heat stroke.(Puser) [15]

Direct contact of body skin to fire flames causes pain when the skin temperature at depth 0.1 millimetre reaches 44° C. Burns, then incapacitation occur which may result in severe injury or death. Inhaled irritant smoke products cause thermal burns to the respiratory tract at around 120° C and may also lead to incapacitation or death.

Exposure to Toxic Gases

Toxic gases such as Carbon Monoxide (CO), Carbon Dioxide (CO2), and Hydrogen Cyanide (HCN) are considered the most hazardous gases because they reach untenable concentrations in the upper layer earlier than the other toxic gases produced from a burning piece of upholstered furniture.

Appendix A contains tables showing the effects on an individual when exposed to the highly toxic gases; Carbon Monoxide and Carbon Dioxide. A table showing the effects on the individual when exposed to different levels of Oxygen depletion, is also included.

Chapter 3
Methodology

The International Organisation for Standardisation (ISO), and the British Standards (BS), considered the NORDTEST / ISO room as an international standard method to describe the fire behaviour of products under controlled laboratory conditions and for fire hazard assessment. The ISO room and the procedure performed in the British Standards have been adopted in this research. The following section briefly sets out the rationale for this choice.

3.1 Development of Full-scale Room Fire measurements

Fire property measurements within a full-scale laboratory environment using controlled tests have historically gone through several stages. The early experiments considered the average room temperature as the only important property to measure. However later, the heat-release rate was recognised as the most significant fire property to be measured. Later with the development of fire research and the appearance of fire plume theory, it was found useful to measure other fire properties such as mass-loss rate, smoke generation rate, rate of entertained air, hot layer temperature, vent flow, and many other properties.

The development of furniture calorimeters allowed the measurement of the heat-release rates from upholstered furniture such as chairs to be done based on the principle of oxygen consumption. Instrumentation provided in the exhaust duct allowed for the measurement of smoke-flow rates and the sampling of toxic gases to predict the concentration of each one of these gases in the smoke-flow produced.

3.2 Existing Full-scale Room Fire Techniques

Efforts to develop a standard full-scale fire-test room, have been summarised by (Babrauskas) [2]. The first successful attempt was, The Monsanto Room followed by the ASTM Room, and finally the latest standard ISO- Room. The Monsanto Room is a cubicle room with 2.7 metre sides and was constructed at Monsanto Chemicals in the late 1970s. Thermocouples were used in the gas space, the walls, and the exhaust duct was used for temperature measurements. An empirical correlation was used to calculate the heat-release rate relative to the different temperature measurements. A small vent was used to supply forced air into the room. Three pool fires of diameter 0.3 metres, 0.6 metres, and 0.9 metres were tested. The ASTM Room is a room with, floor dimensions 2.4 metres x 3.7 metre and a height of 2.4 metres was constructed with a door opening 0.76 x 2.03 metres. A standard gas burner ignition source of 176kW was used. A complex exhaust system was specified. The concept of measuring the heat- release rate based on oxygen consumption was used. The burning rate of combustible room linings such as the floor, wall, and ceiling were measured based on oxygen consumption.

3.3 The NORDTEST / ISO Room

Room Description

This is the current standard room with dimensions measuring 3.6 meters length, 2.4 metres width, and 2.4 metres height. The door dimensions were 0.8 of a metre wide and 2.0 metres height. The room is constructed of non-combustible material with a density of 500-800 kg/m³. The minimum thickness of the construction was 20 millimetre. Figure 1: shows the ISO Room as described in the British Standards.

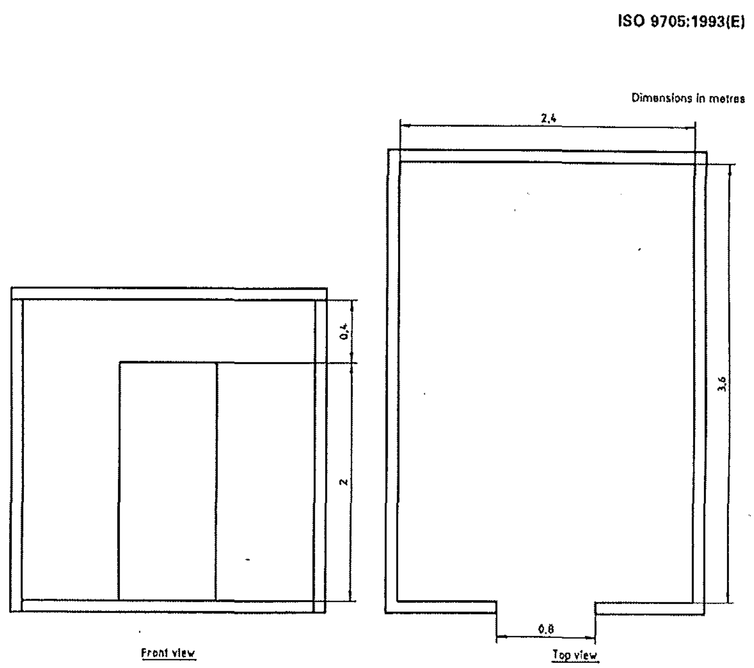

Figure 1: ISO Room (from British Standard)

3.4 Experimental Set-up used for this research

A room identical to the ISO room was built inside the School of Engineering Fire Laboratory, Canterbury University, Christchurch. Figure 2 is a plan of the fire laboratory and shows the location of the fire-test room inside the laboratory. A photo of the fire-test room inside the fire laboratory and the exhaust hood can be seen in figure 3.

The Oxygen consumption calorimetry was used for calculating the heat-release rate from the species measurements of oxygen, carbon dioxide and carbon monoxide. That was based on the constant net amount of heat to be released equal to 13.1 KJ per unit mass of one gram of oxygen consumed, and converting the measured mole fractions to mass fractions by multiplying the mole fraction with the ratio between molecular mass of oxygen (~ 28 g/mole) and molecular mass of the gas sample.

A square ignition source of heat output measuring 30 kW was used, and is shown in figure 4. One vertical array of thermocouples was used to measure the temperature profile inside the room and a heat-flux calorimeter, which will be described later in the room construction and instrumentation sections. The mass-loss of burning items was measured during the experiments using an electronic scale.

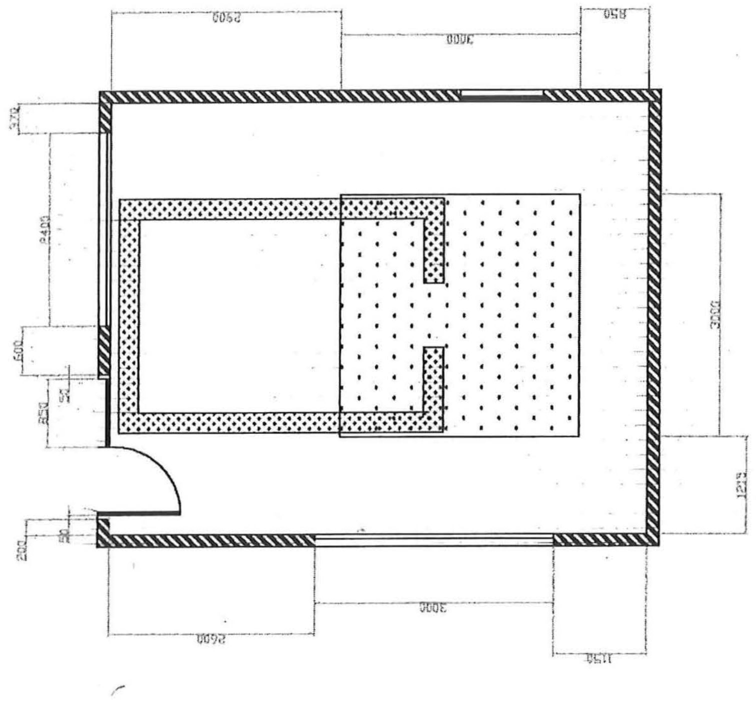

Figure 2: Plan of School of Engineering Fire Laboratory and the Location of Fire-test Room.

Figure 3: Photograph of the Fire-test Room and the Exhaust Duct

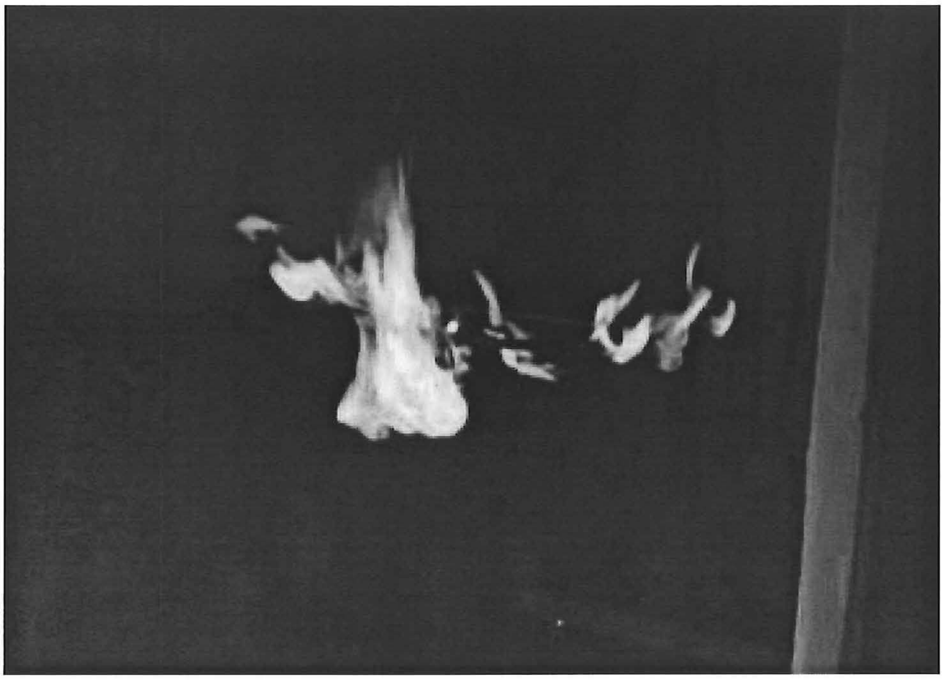

Figure 4:Photograph of the ignition source

3.5 Room construction

The fire laboratory is separated from the rest of the building by a two hours fire separation. The control room, where the experiments are controlled and supervised after ignition is also separated from the laboratory by a two hours fire separation. Figure 5 is a photo showing the fire test room inside the laboratory. In addition further precautions were taken by installing a manually operated sprinkler inside the laboratory, just above the door of the fire-test room. The location of the room was chosen to allow safe and easy movement inside the laboratory area during the experiments. The height of the exhaust duct from the laboratory floor is 2.97 metres allowing for a clearance height of 300 millimetres between the floor of the fire-test room and the laboratory.

Treated building timber of 100 millimetres x 50 millimetres cross section was used for the room framing. The floor, walls, and roof frame studs were built at approximately 600 millimetres distance as shown in figure 6. Timber bracing was added where needed to the room for structural stability. Figure 7 is a cross section of the fire-test room framing. A permanent layer of 12.5 millimetre plywood sheets was used on the floor, and 12.5 millimetre fire-rated gib boards were used on the walls and ceiling.

These layers were then sealed using gib plaster and tape on both sides. The internal surfaces floor, ceiling and walls, were covered by extra 12.5 millimetre fire-rated gib boards, and also sealed. One hundred millimetre nails were used for the framing joints, and 40 millimetre screws were used to secure the plywood sheets to the floor, and the internal layer of the first fire-rated gib boards on the walls and ceiling. Sixty millimetre screws were used for the top fire-rated gib boards.

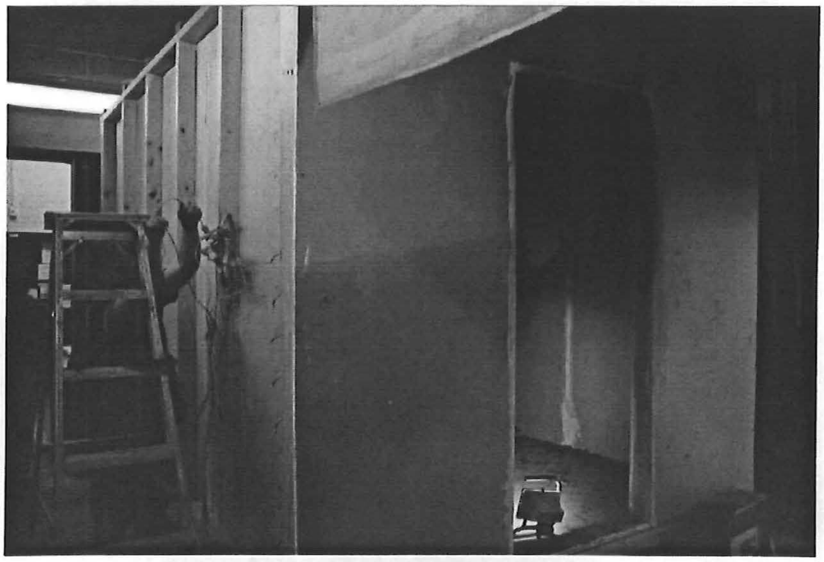

Figure5: Photograph of the ISO Room (as built in the Fire Laboratory, Canterbury University).

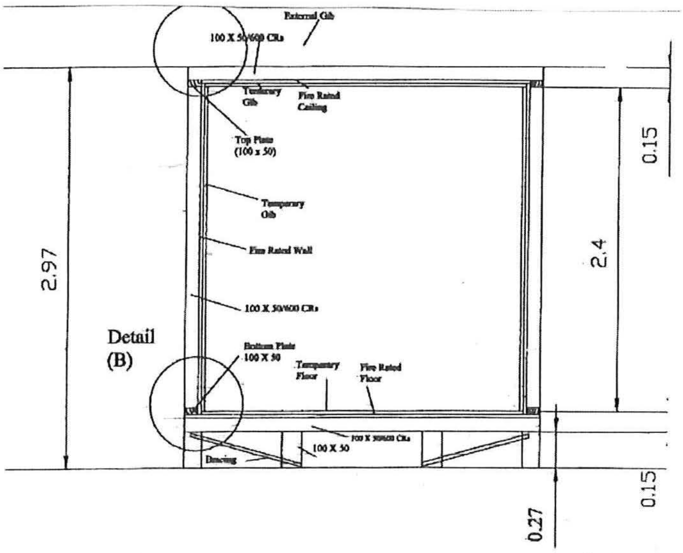

Figure 6: Construction details and cross section of the room framing.

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3.6 Instrumentation

Thermocouples

An array of thermocouples was installed vertically up the inside of the left- hand sidewall (see figure 7, which shows the schematic thermocouple array relative to the fire-test room door. The array is positioned 150 millimetres from the door wall. The first thermocouple was positioned 75 millimetres from the floor and each following thermocouple at 150 millimetre intervals with the last one located a 75 millimetres from the ceiling.

The thermocouples used were type K Chromel-Alumel 0.5 millimetre diameter, with an approximate bead size of 1millimetre, and were protected inside a 6 millimetres steel tube, the end of which the thermocouples protruded approximately 50 millimetres from the end of the steel tube. The steel tube was inserted into the wall through a hole, which had been drilled into the two layers of the gib wall. Screws were used through the steel tube flanges to hold the steel tubes in the required positions; the thermocouples were then connected to the data acquisition equipment.

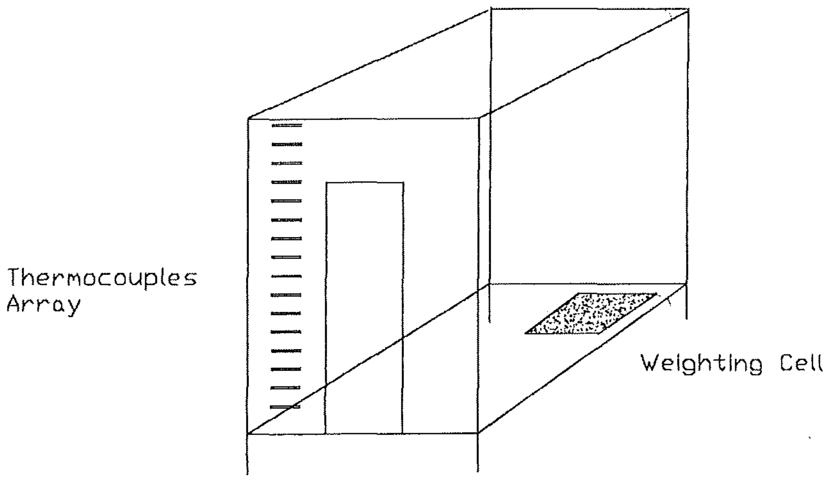


Figure 7: Schematic of Thermocouples Array.

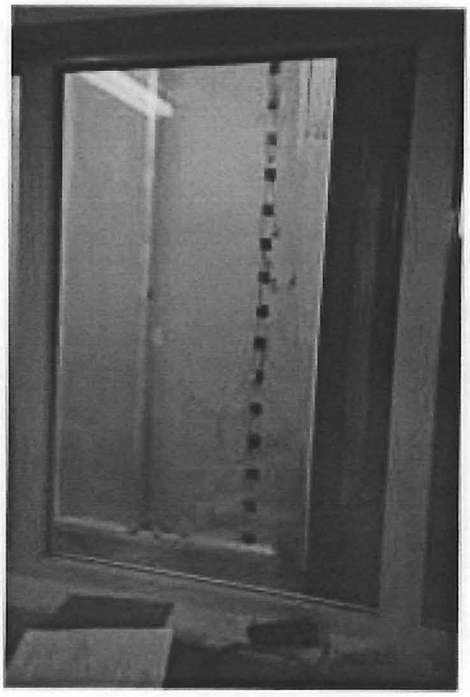


Figure 8: Outside Photograph for the Thermocouple Array.

Scale

An electronic load cell was used to measure the mass of the burning chair during the experiments. It was placed at the far right corner from the room door, where the chair was tested. The scale consists of two identical one metre square steel plates. The upper plate was placed on the fire-test room floor and the lower plate was placed on the fire laboratory floor covering the electronic loading cell. A hole of approximately 50 mm diameter was drilled in the floor corner where the chair would burn. Four steel bars of the lower steel plate were inserted inside four steel tubes of the upper plate so that the two plates acted as one unit. The lower plate was connected to a digital meter, and plugged into a power point.

The scale was then calibrated and zeroed, and connected to the data collection equipment. Figure 9 is a Schematic of the Electronic Weighting Cell.

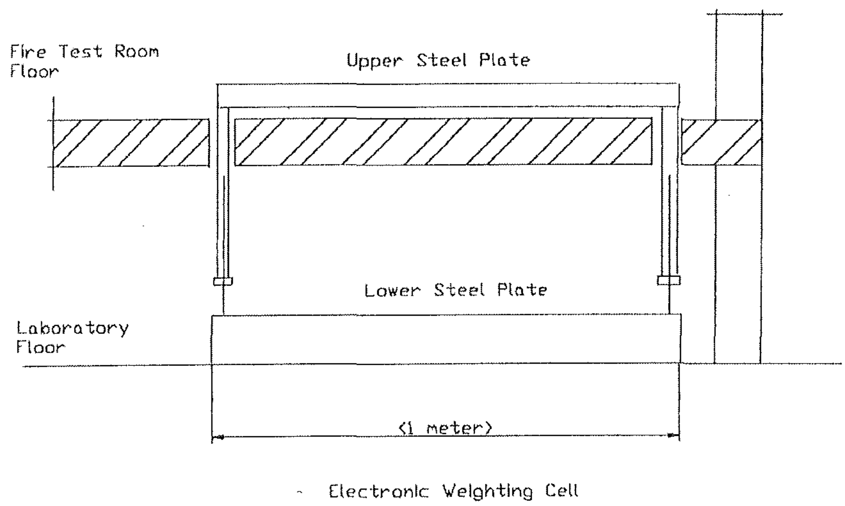


Figure 9: Schematic of the Electronic Weighting Cell

Heat-Flux Calorimeter

Figure 10 is a photograph showing the heat-flux calorimeter, which was placed at the centre of the fire-test room floor. A 50 millimetres diameter hole was drilled in the floor centre. The heat-flux calorimeter was inserted from underneath the room floor and then connected to the water tape by a small copper tube to provide a slow water flow to the calorimeter. Another small copper tube was used to drain the water to an outlet on the laboratory floor. Then the heat-flux calorimeter was connected to the data acquisition equipment.

Video Equipment

A video camera was placed at approximately 1.5 metres outside the fire-test room door at an angle to provide a clear view through the door opening of the development of the burning chair. The camera was protected inside a timber-framed box covered by gib boards. A small piece of heat resistant glass positioned on one side of the box provided a clear view into the fire-test room. A digital clock was placed beside the fire-test room door to record the time during the fire development. This was recorded in the videotape.

A second video camera was placed inside the control room, positioned towards the window that separates the fire laboratory and the control room to provide a clear view of smoke movement through the door opening of the fire-test room and into the exhaust hood.

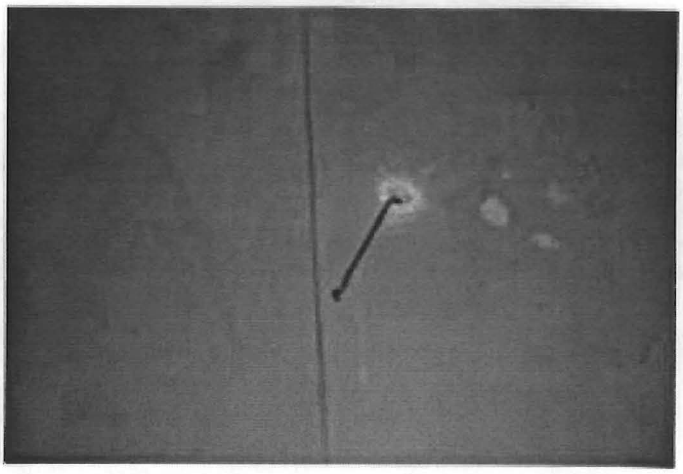


Figure 10: Photograph of the Heat Flux Calorimeter

Gas Analysis Equipment

The laboratory was equipped with facility for a smoke extraction system with a fan capacity of 4 m^3/sec. This system was used for both smoke capture and as an exhaust system for the experiments and functioned by drawing the smoke from the room through its door opening to an exhaust hood which measured 3 metres x3 metres x 0.8 metre. The smoke was then transported to the exhaust duct to pass through soot and tar filtering, then through a cooling unit to condense the water vapour. The smoke then passed through a carbon dioxide, a carbon monoxide, and an oxygen analysers.

Exhaust Hood Extension

After running the first two experiments, it was decided to drop a curtain around the exhaust hood to control the smoke movement towards the exhaust duct, when it was found that some of the smoke travelled away from the hood. The curtain consisted of fire-rated thick fabric with a drop of one metre; it completely surrounded the exhaust duct.

Data Acquisition Equipment

An analogue to digital converter installed within a personal computer was used to collect data. Data in all channels was captured 5 times per second and then averaged over 5 readings to give an average value per second. Figure 11 is a photograph of the data acquisition and gas analysis unit used for the experiments.

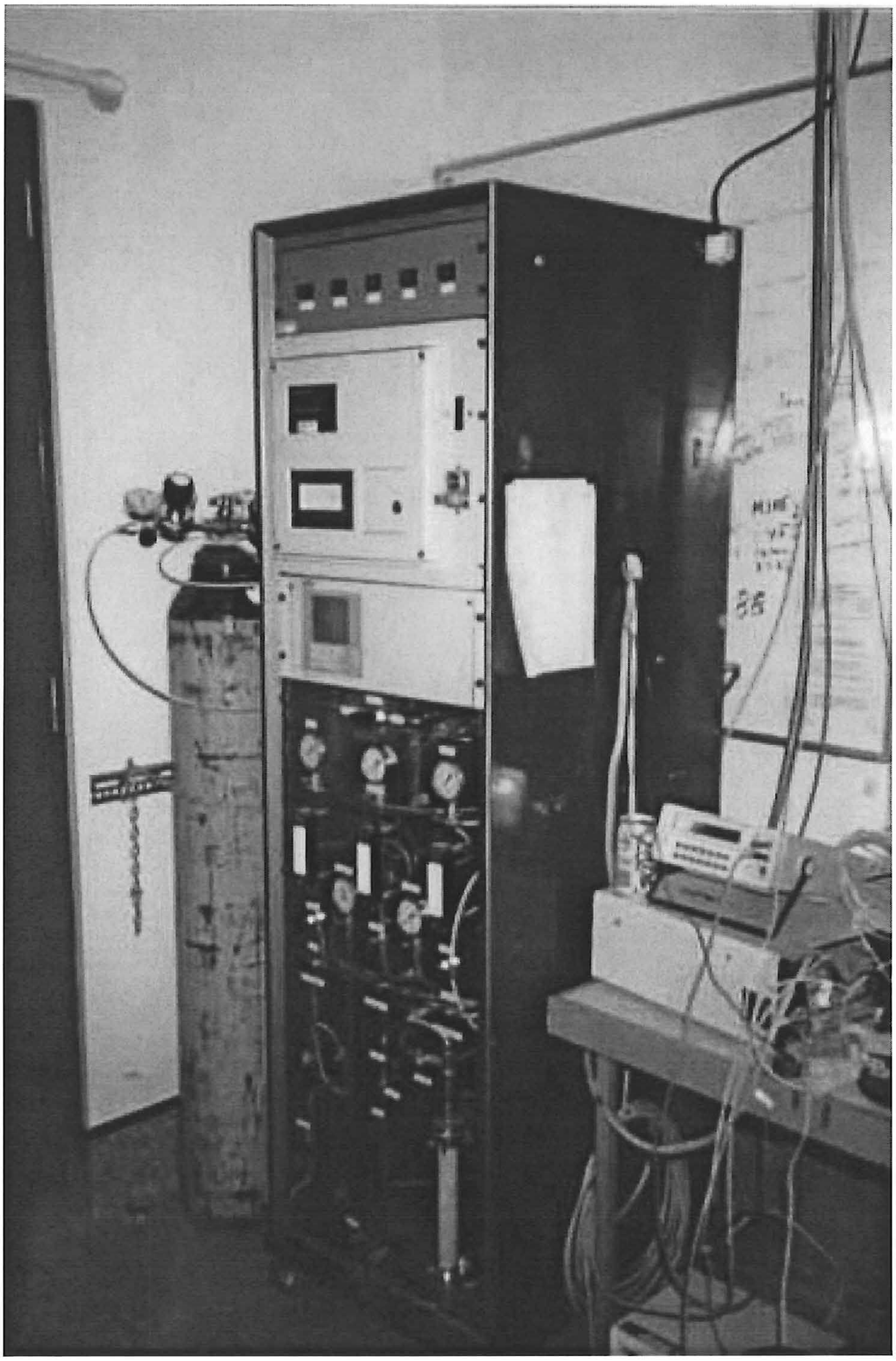


Figure 11: Photograph of the Data Acquisition & Gas Analysis Equipment.

3.7 Tested items

The tested items consisted of six upholstered chairs, commercially built for the experiments, each built with the same design, size, and covering fabric. However, different cushioning foams were selected for each chair as shown in table 1. Under category 'chair code', 21, refers to the fabric type used, and S2 refers to single chair tested in the CBUF # 2. Different foam categories for each chair is shown in the table.

Chair Number	Fabric Type	Foam type	Chair Code
Item 1(Chair # 3)	21	G	21-G-S2-1
Item 2 (Chair # 7)	21	H	21-H-S2-1
Item 3 (Chair # 10)	21	I	21-I-S2-1
Item 4 (Chair # 13)	21	J	21-J-S2-1
Item 5 (Chair # 16)	21	K	21-K-S2-1
Item 6 (Chair # 19)	21	L	21-L-S2-1

Table 1: Fabric and Foam Types for each Item.

(Note: Foams coded H and J, which were used for both item number 2 (Chair number 7) and item number 4 (Chair number 13) respectively had a fire retardant added).

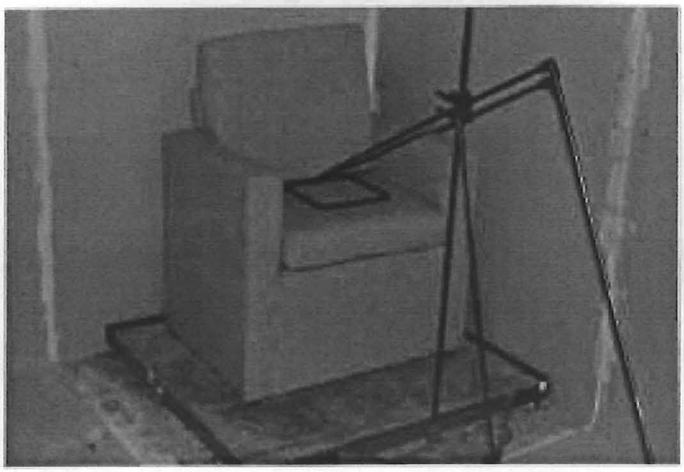


Figure 12: Photograph of Chair Style

3.8 Running the Experiments

Six experiments were conducted so that each item was burned separately under the same laboratory controlled conditions as the others. It was necessary to replace and seal the wallboards after conducting each experiment run to maintain identical conditions and interaction between the items and the room.

A complete record of all the experimental measurements was kept at the University of Canterbury, Civil Engineering Department (Fire Engineering), together with a video taped recording of each experiment run.

Experiments were conducted over six days, each day testing one single upholstered chair. (Note in table 2, summary of experiments, that items 1 and 2 were not chosen in consecutive order).

Experiment No.	Date	Item No.	Chair No.	Chair Code
Experiment # 1	3/12/1999	2	7	21-H-S2-1
Experiment # 2	6/12/1999	1	3	21-G-S2-1
Experiment # 3	7/12/1999	3	10	21-I-S2-1
Experiment # 4	8/12/1999	4	13	21-J-S2-1
Experiment # 5	9/12/1999	5	16	21-K-S2-1
Experiment # 6	10/12/1999	6	19	21-L-S2-1

Table 2: Summary of the Experiments.

According to the experiment protocol the chairs were conditioned inside the temperature control room at 25°C, 50 % RH for 14 days prior to the experiments.

The laboratory supply of the Liquid Propane Gas (LPG Fuel) was checked prior to the first experiment run, using the existing standard laboratory burner. This was to ensure that the ignition source was in working order. The airflow through the fire laboratory was checked prior to the first experiment run. The instrumentation and all other measuring equipment were also checked after each run.

The exhaust fan capacity and the smoke flow through the duct was checked prior to each run to ensure reliable sampling of the smoke species. Lime to protect smoke damage was loaded into the filter bags before each run. The air bags in the line were checked and some of these needed cleaning. Also, calibration of the weighting scale was tested prior to each run.

The replacement of the internal fire-rated gib boards, after each run necessitated the removal and reinstallation of the thermocouples, and the heat-flux calorimeter. Before each new run the thermocouples and heat flux calorimeter were checked for possible damage. The collection of the data was started at a three minutes baseline prior to each run to measure the ambient condition and to check that there was a reading for all measurements taken.

Finally the standard procedure recommended by the British Standard, BS.476: Part 33: 1993; ISO9705: 1993 (Fire tests on building materials and structures, Part 33. Full-scale room test for surface products)," corner test" was followed.

Chapter 4
Results

Data recorded from the experiments for each chair were heat-release rate, heat-flux, temperature-profile and temperature-history inside the fire-test room, also the mole fractions of carbon monoxide, carbon dioxide and oxygen inside the exhaust duct. The mass-loss rate of the burning chairs was measured. Data is presented in graphs and tables.

One typical run, namely experiment number six, will be discussed in detail in this chapter with a brief exploration of the fire development as observed during the experiment and from the recorded videotape. Following that is a comparison between

4.1 Experiment Number six

This experiment tested chair number 19, which was coded (21-L-S2-1). The procedure followed in this experiment was a typical run similar to the other runs. The burning chair was placed at the far right hand side corner from the room door of the ISO room with floor dimensions 3.6 metres x 2.4 metres. However, at early stages of the experiment the flames were seen coming out of the room door and a huge amount of black smoke was produced within a few minutes containing carbon monoxide and carbon dioxide in high levels of concentration, which went beyond the tenability limits. Most of the extra internal gib boards were turned to powder and became very soft boards.

Data collecting equipment was started 3 minutes prior to ignition of the chair. Ten seconds after ignition of the chair, the arm rest and the back of the chair were in flames. Fifteen seconds from ignition, light started to appear from the outside fabric of the arm rest, and 20 seconds from ignition this outside fabric of the arm rest was totally burned. Flames were evident from all chair parts at 50 seconds after ignition, At this time, the layer of hot black smoke was estimated to have reached a thickness of approximately 1.3 metres. The height of the chair where ignition occurred was around 570 millimetres from the floor (the chair having been placed on the upper steel plate of the weighing cell with an approximate height of 50 millimetres above the floor). However, at 75 seconds from ignition, flames, with an average height of 1.5

metres from the floor, had started from all the lower parts of the chair. Ten seconds later (85 seconds from ignition) the average height of the flames was approximately 2 metres from the floor. At 95 seconds from ignition black smoke filled more than half of the room. Smoke then started to accumulate rapidly and pass through the door opening. At 100 minutes after ignition flames started to appear through the door opening. At 120 seconds from ignition some wall boards, those closest to the chair, were heated sufficiently to produce flames. However, 20 seconds later the chair fire started to decay otherwise the fire-test room itself might have been involved in the fire.

During the decay stage and up to six minutes from ignition the foam was totally burned. However the timber frame of the chair was still burning without collapse. The experiment and data collection continued for 26 minutes from start. Then the collection of the data stopped. Figure 13 is a series of photographs of the experiment for chair number 19. These show the fire development at approximately 15 seconds intervals and the room conditions both before and after running the experiment.

Figure 13: Fire Development of Chair Number 19 in Photos (Continued)

Figure: 13(Continued)

Figure: 13 (Continued)

Figure :13 (Continued)

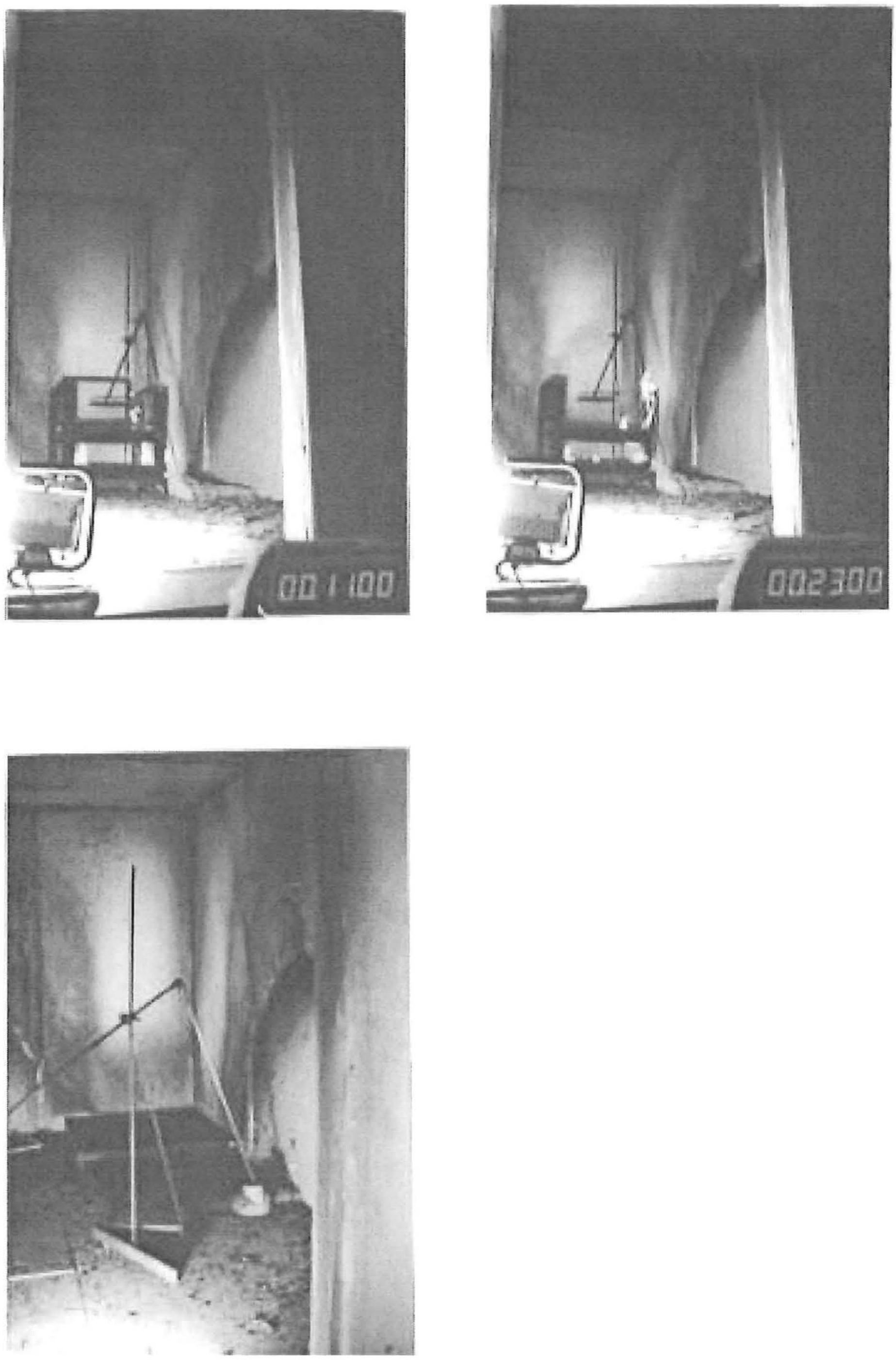


Figure: 13

Figure (14 Part a), the heat-release history for chair number 19, shows that the peak heat-release rate of 1.82 MW was measured after 138.1 seconds (2.3 minutes) from ignition. The heat-flux history for chair number 19, recorded the greatest heat-flux of 0.5031. It was measured after 136.6 seconds (2.3 minutes).

Figure (14 Part b), the compartment temperature-history for chair number 19, shows that a maximum temperature of 646.6 °C was measured after 159.2 seconds from ignition (2.65 minutes).

Figure (14 Part c), the temperature profile history for chair number 19, shows that the maximum temperature at height 1 m from the floor was 581 °C, and the maximum temperature at height 1.8 m from the floor was 645°C.

Figure (14 Part d), the smoke species history for chair number 19, shows the maximum carbon monoxide mole fraction of 0.00748 recorded at 145.8 seconds from ignition (2.43 minutes). Maximum carbon dioxide of 0.0259 was recorded at 148.1 seconds (2.46 minutes) from ignition and a minimum oxygen mole fraction of 0.1781 was recorded at 151.5 seconds (2.5 minutes) from ignition.

Figure (14 Part e), shows that during the period of full fire development, chair number 19 showed a greater amount of mass loss than during any other period of the fire.

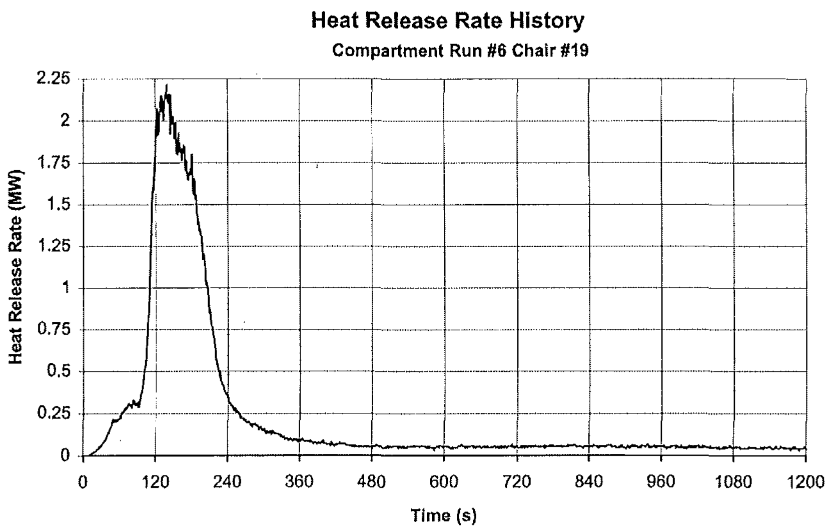


Figure 14 (a): data for chair 19 in Graphs (Continued)

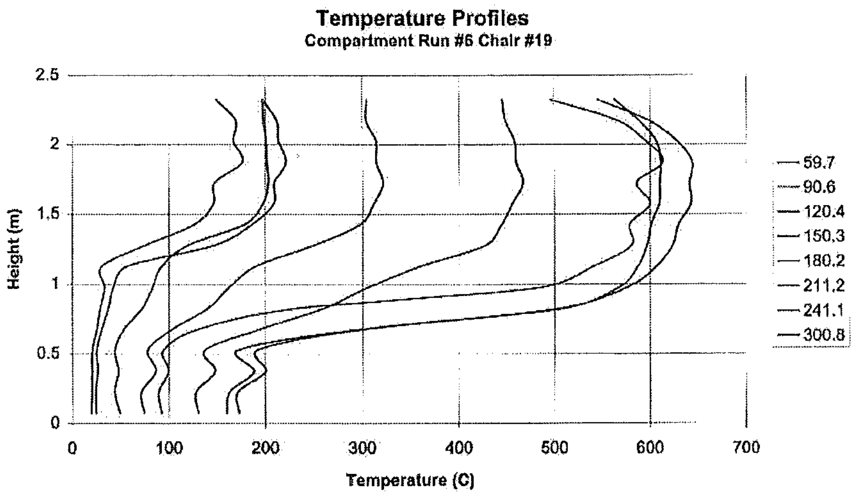


Figure 14 (b): data for chair 19 in Graphs (Continued)

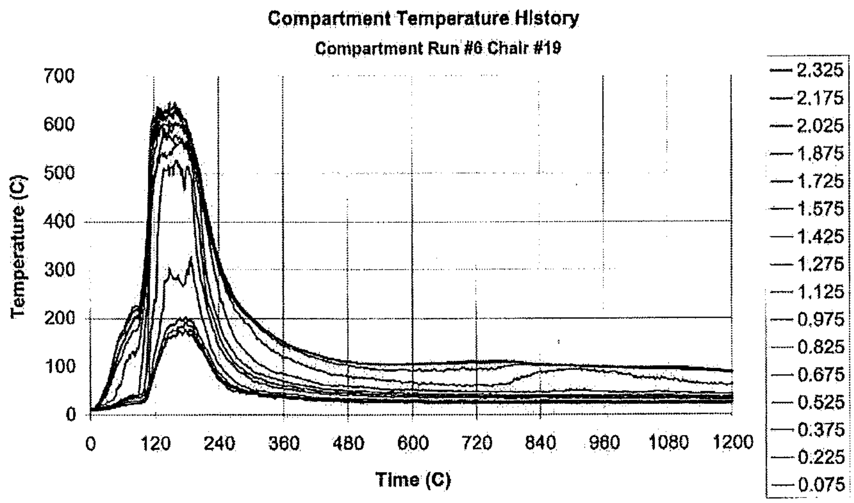


Figure 14 (c).(Continued)

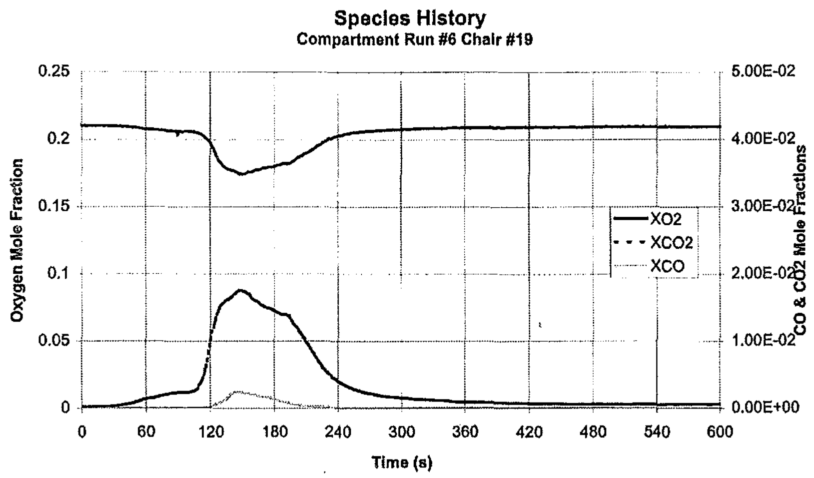


Figure 14 (d).(Continued)

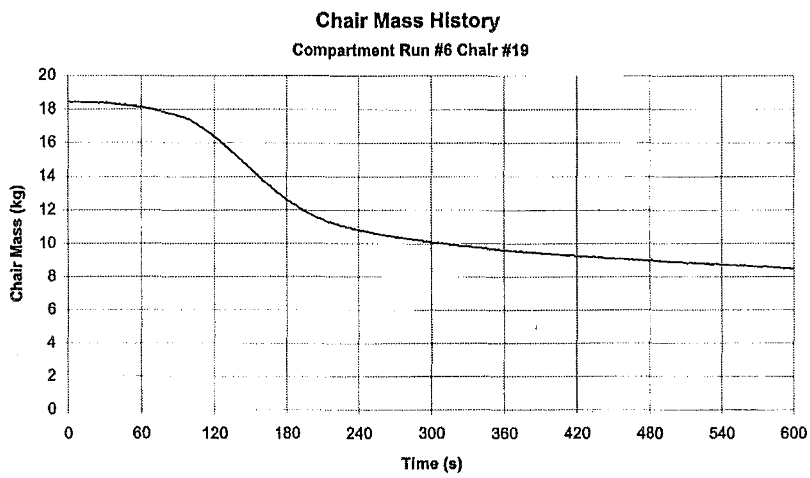


Figure 14 (e).

4.2 Comparison of Results

Comparison between chairs is presented in this section in tables. These examine the effects of using the different types of foams and the hazards produced by each one during the fire.

Different categories might be used to compare between chairs according to points of interests, however only two categories have been considered in this study. Firstly the maximum fire hazard values reached by each chair which indicate the size of the fire hazard parameters. These maximum values are considered too late for an individual in the room of fire origin, however these maximum values might affect the time available for an individual in an other adjacent room to escape from the building. The second category is the value of each fire hazard when the conditions in the room of fire origin become lethal and the individual might not be able to escape. Some other parameters will be considered for smoke species.

4.2.1 Heat-Release Rate

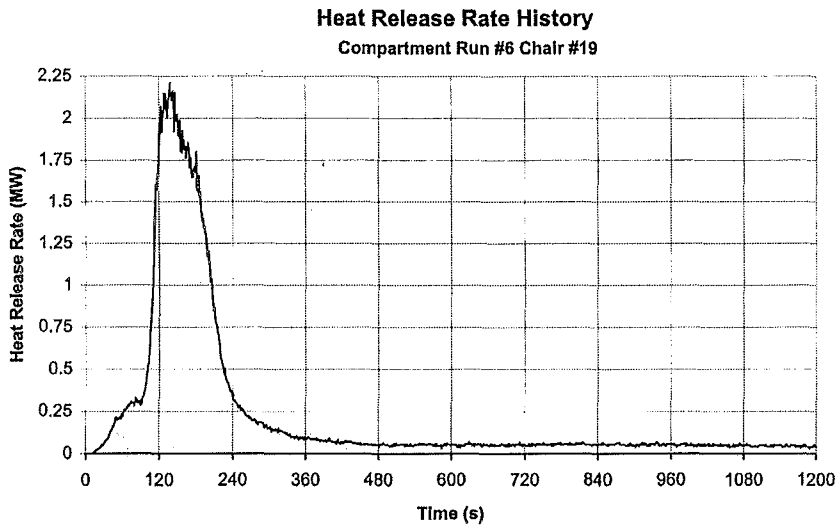
Peak heat-release rate and the time to reach the peak heat-release rate was considered comparing the data obtained from the experiments, which indicate the fire size for each chair in order to classify the behaviour of the six tested foams in fire. Another category considered valuable from a life safety point of view, is the time taken for each chair to reach 500 kW, when the fire has a rapid growth. Table 3 is a summary of Heat-Release Rate data. Figure: 15 shows the heat-release rate history curves of chairs: 19, 16, 13, 10, 7, and 3 respectively.

Item	Peak HRR (MW)	Time for Peak HRR (sec)	Time for 500 kW (sec)
Item 1 (Chair # 3)	1.45	184.3	130.0
Item 2 (Chair # 7)	1.34	196.3	159.0
Item 3 (Chair # 10)	1.56	144.0	104.5
Item 4 (Chair # 13)	1.52	210.4	162.8
Item 5 (Chair # 16)	1.59	136.0	96.5
Item6 (Chair # 19)	1.82	138.1	102.7

Table 3: Heat-Release Rate

Peak Heat-Release Rate: The heat-release rate measured for different tested types of foam varied from 1.82 MW produced by chair number 19 at 138.1 seconds from ignition, to 1.34 MW produced by chair number 7 at 196.3 seconds from ignition. The variation of 0.48 MW was found. Time to reach Peak Heat-Release: Time to reach peak heat-release from different tested types of foam varied from 138.1 seconds from ignition for chair number 19 to reach 1.82, to 210.4 seconds from ignition for chair number 13 to reach 1.52 MW. This gave a variation of 72.3 seconds.

Chair number 16 reached its peak heat-release rate before chair 19, however, the difference was only two seconds while the difference in heat- release rate was 0.23 MW, therefore chair number 19 was chosen as the fastest chair.



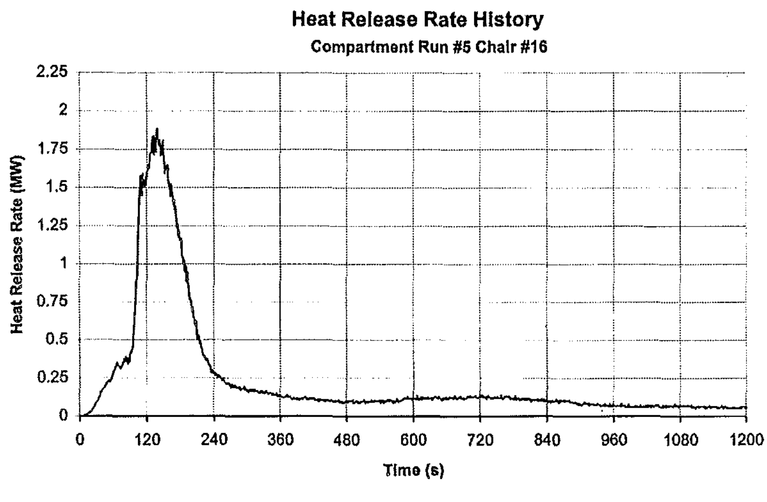
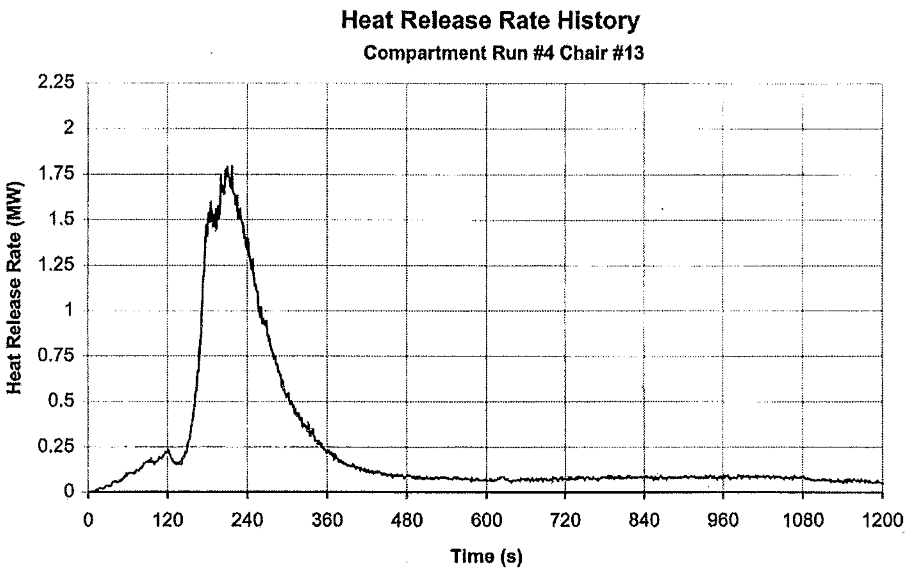


Figure 15: Heat-Release History (Continued).



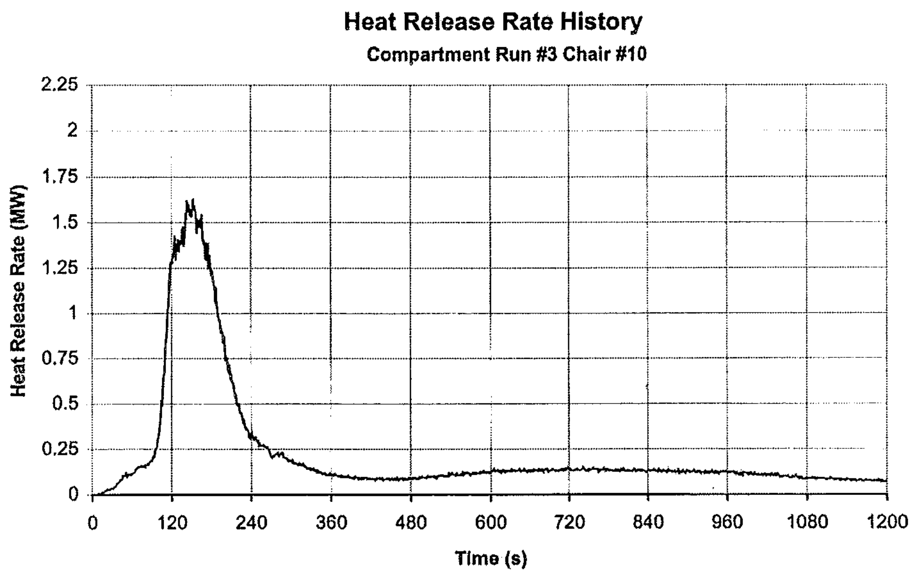
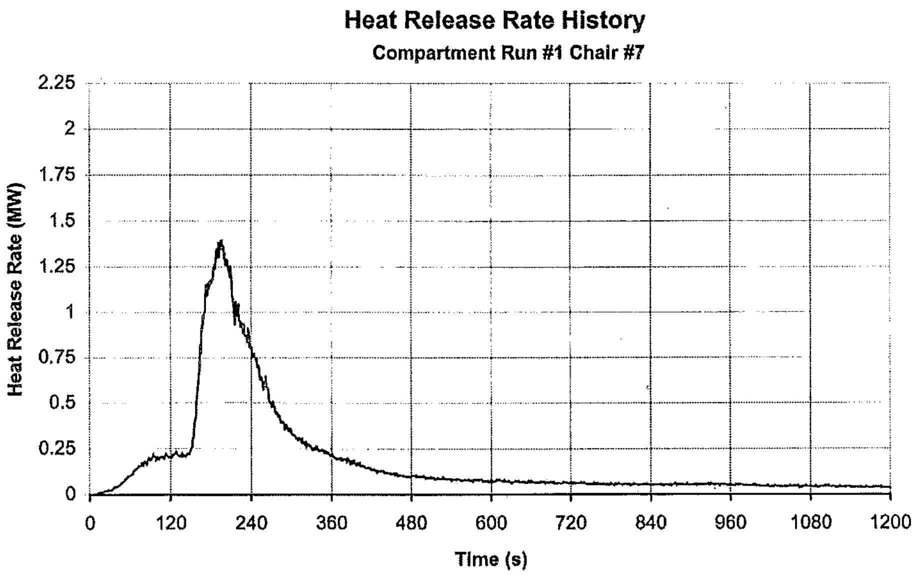


Figure: 15 (Continued)


Heat Release Rate History
Compartment Run #1 Chair #7
Heat Release Rate (MW)
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
120
240
360
480
600
720
840
960
1080
1200
Time (s)

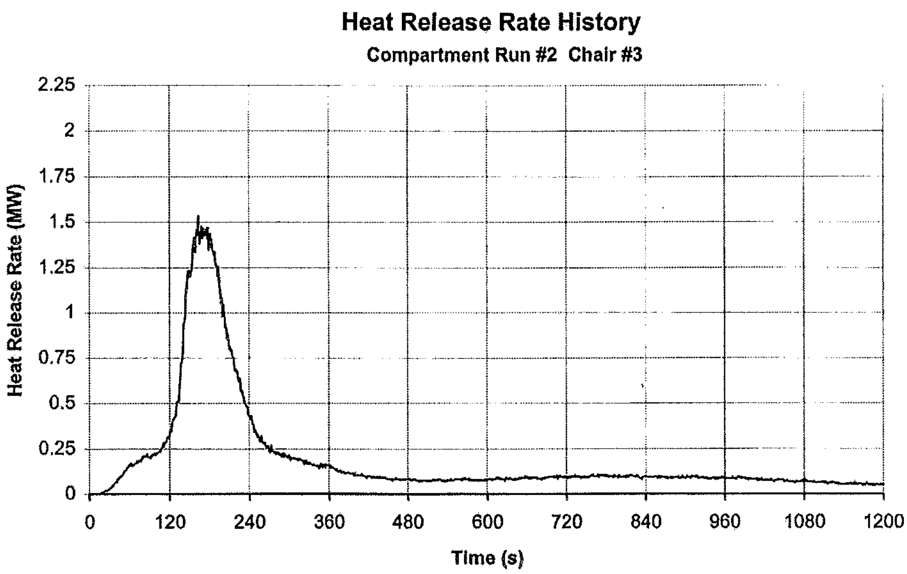

Heat Release Rate History
Compartment Run #2 Chair #3
Heat Release Rate (MW)
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
120
240
360
480
600
720
840
960
1080
1200
Time (s)

Figure: 15

4.2.2 Temperature Profile

One vertical array of thermocouples was placed 150mm from the door wall, as described in chapter three section 3.6. Figure 16: shows the room temperature profile history for chairs 19, 16, 13, 10, 7, and 3 respectively. As the temperature varied from one point to another inside the room, two points were selected to compare between chairs, as in Table 7.

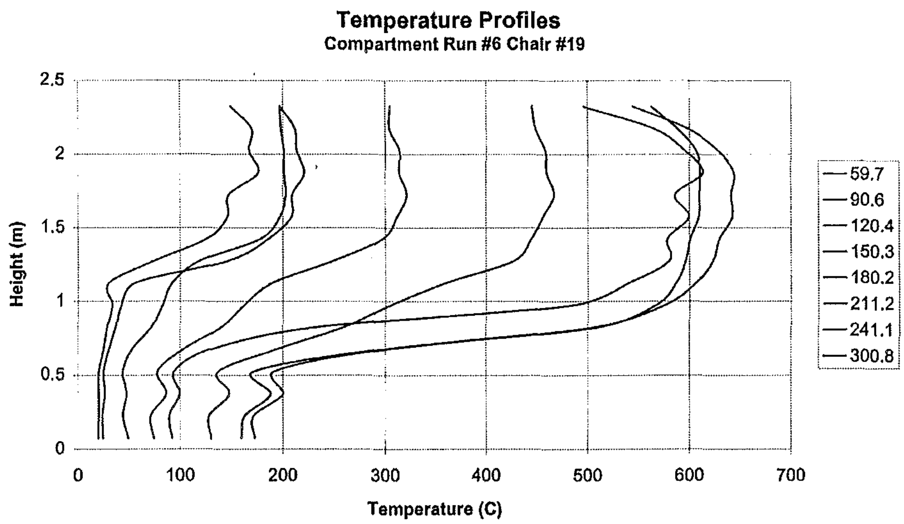
Item	Maximum Temperature at 1.0 m from the floor °C	Maximum Temperature at 1.8 m from the floor °C
Item 1 (Chair # 3)	572	640
Item 2 (Chair # 7)	500	572
Item 3 (Chair # 10)	545	631
Item 4 (Chair # 13)	531	631
Item 5 (Chair # 16)	507	645
Item 6 (Chair # 19)	581	645

Table 4: Temperature Profile

From Table 4

The highest temperature of the selected points at 1 metre above the floor occurred from chair number 19, and the lowest maximum temperature of the selected points at 1 metre above the floor occurred from chair number 7. The temperature variation between these two chairs at 1metre was 81 °C. The highest temperature at 1.8 metres above the floor occurred from chair number 19 and chair number 16, and the lowest maximum temperature at 1.8 metres above the floor occurred from chair number 7. The temperature variation at 1.8 metres above the floor was 72 °C.

Although the reading of one array of thermocouples might not be sufficient to give an accurate figure for the temperature profile inside the whole room, it was considered sufficient for the purpose of comparison between the nominated chairs.



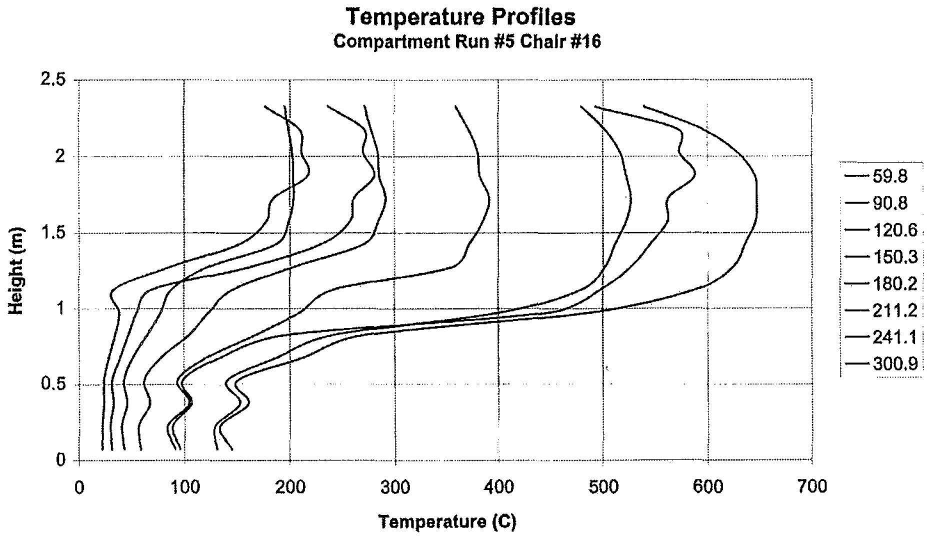
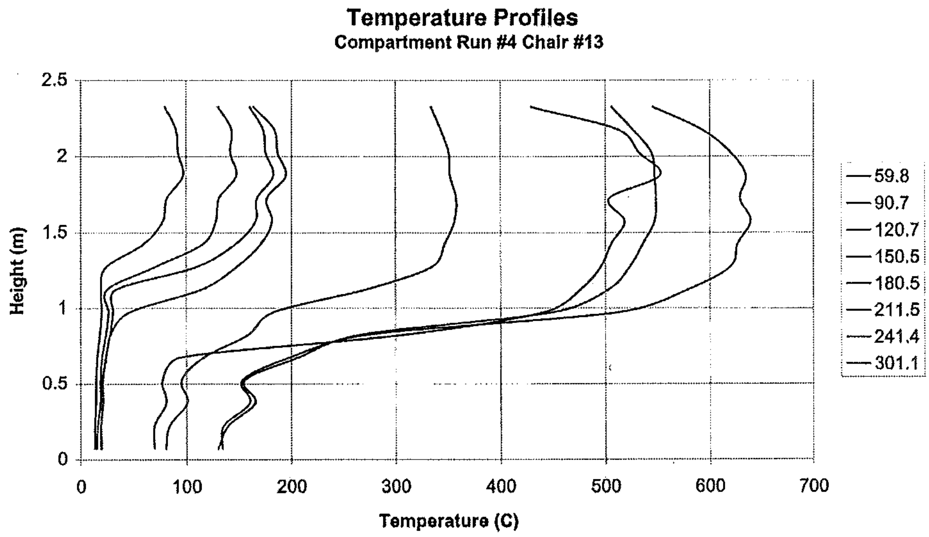


Figure 16: Room Temperature Profile History (Continued)



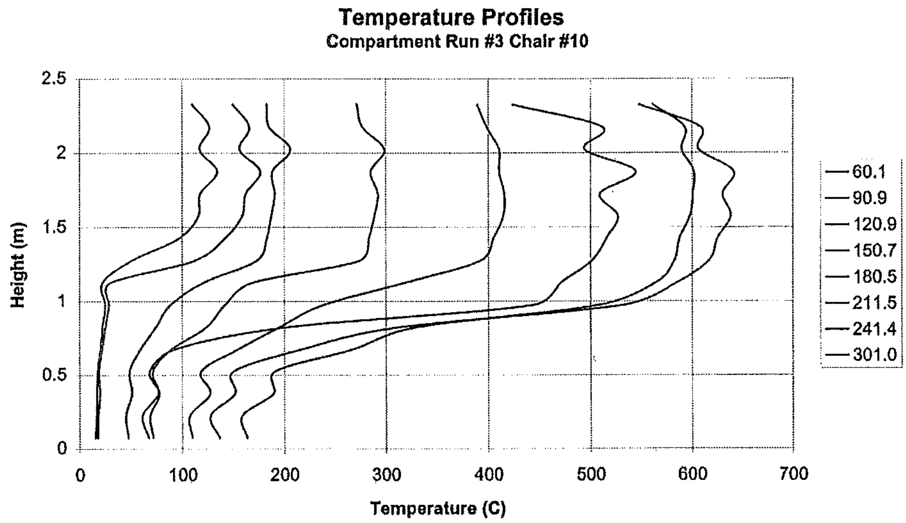
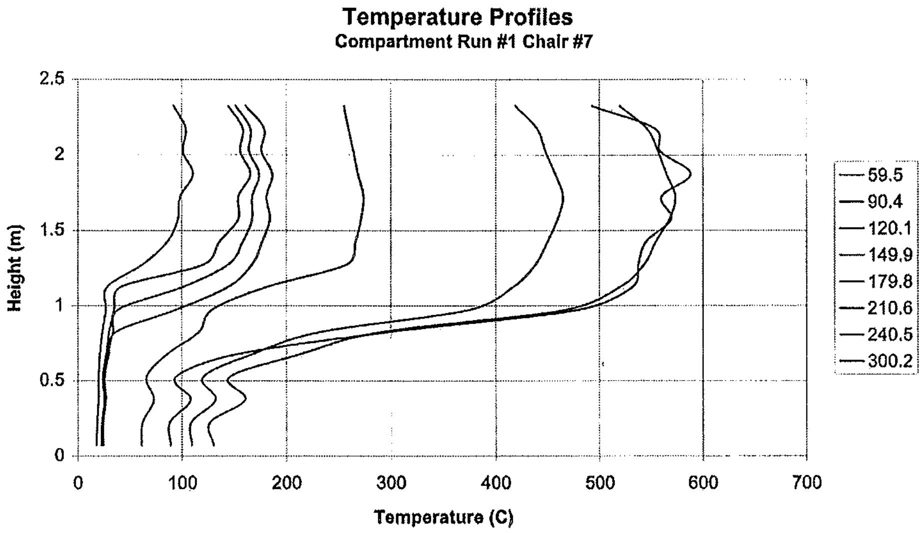


Figure :16 (Continued)



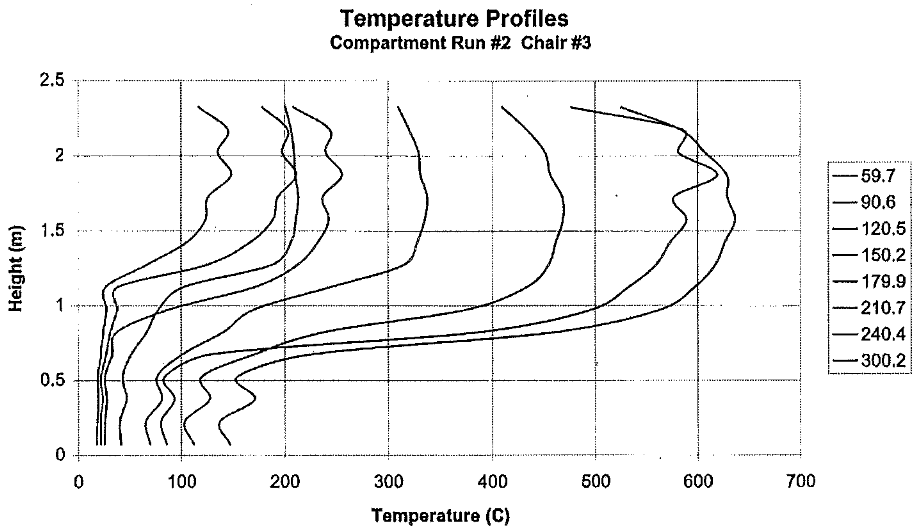


Figure: 16

4.2.3 Compartment Temperature

The compartments temperature history curves of the six chairs are presented in figure 17. The maximum room temperature reached and the time taken to reach this maximum temperature is presented for each chair in Table 5.

Item	Maximum Room Temperature °C	Time to reach Maximum Room temperature (sec)
Item 1 (Chair # 3)	656.3	155.8
Item 2 (Chair # 7)	643.3	191.9
Item 3 (Chair # 10)	674.2	142.9
Item 4 (Chair # 13)	656.9	210.5
Item 5 (Chair # 16)	664.9	138.2
Item 6 (Chair # 19)	646.6	159.2

Table 5: Room Temperature

Maximum Compartment Temperature

The maximum measured temperature of 674.2 °C was recorded from chair number 10 at 142.9 seconds from ignition, while the maximum measured temperature of 643.3 was recorded from chair number 7 at 191.9 seconds from ignition. A variation of 30.9 °C was found.

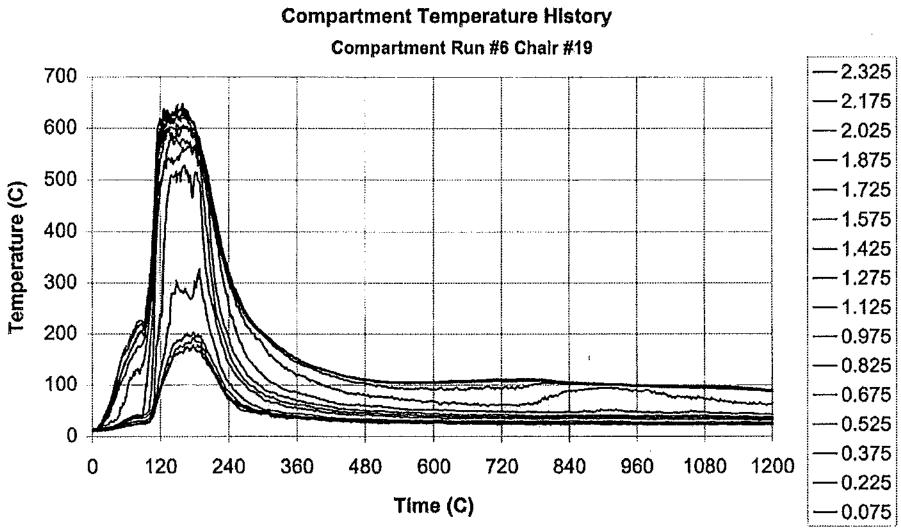
Time to reach Maximum Compartment Temperature

Chair number 13 reached a maximum compartment temperature of 656.9°C in 210.4 seconds This was the slowest. Chair number 10 reached its maximum compartment temperature of 674.2 °C in 142.9 seconds indicating a significant variation of 67.6 seconds.

The difference between the maximum temperature in the room for all six chairs was not great, however, there was a significant variation in time to reach the maximum temperature. Referring to the tenability limits, for an individual inside the room of fire origin, time taken for the temperature to reach 120 °C at 1.6 metres, and time to reach 500 °C average upper layer temperature.

Item	Time to reach 120 °C at 1.6 m from the floor (sec)	Time for 500 °C average upper layer temperature (sec)
Item # 1 (Chair # 3)	59.0	145.5
Item # 2 (Chair # 7)	73.0	137.1
Item # 3 (Chair # 10)	62.5	122.0
Item # 4 (Chair # 13)	85.5	180.0
Item # 5 (Chair # 16)	43.5	105.0
Item # 6 (Chair # 19)	50.0	112.0

Table 6: Temperature Tenability Limits.



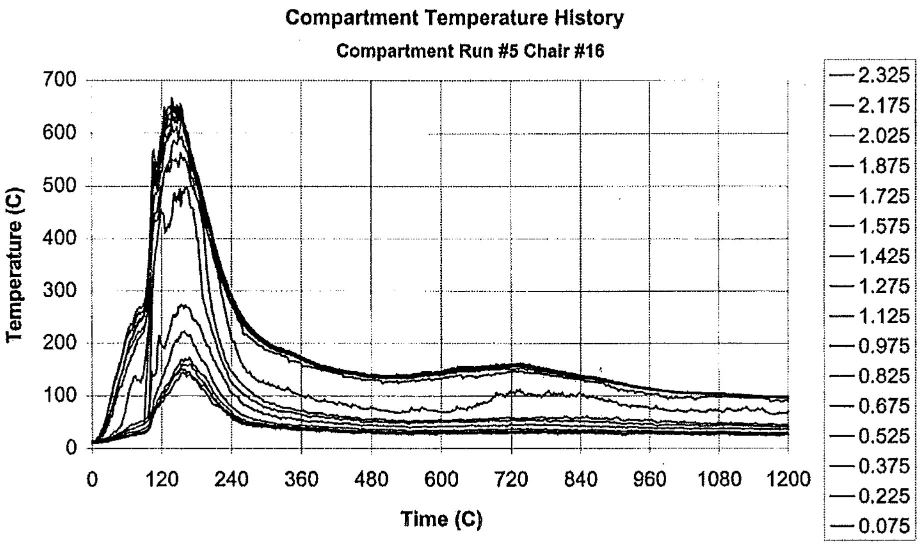
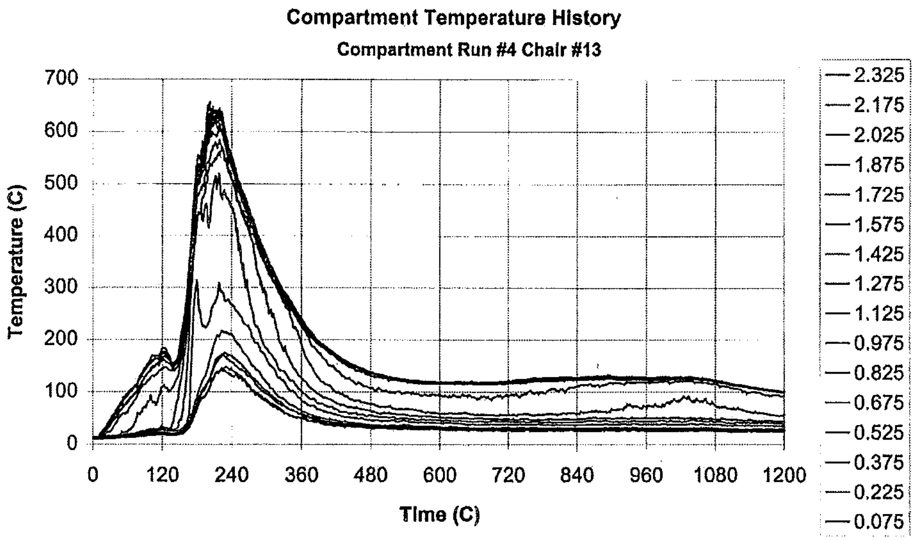


Figure 17: Compartment Temperature History(Continued)



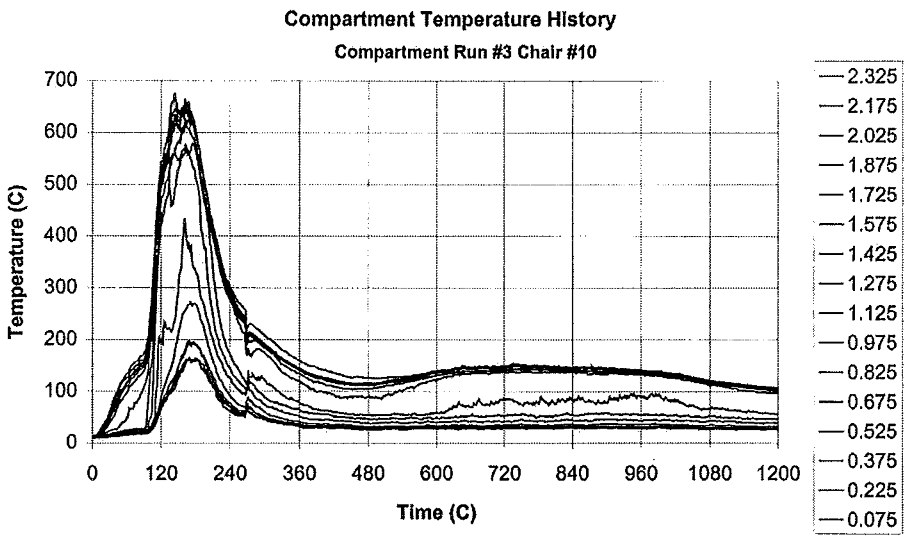
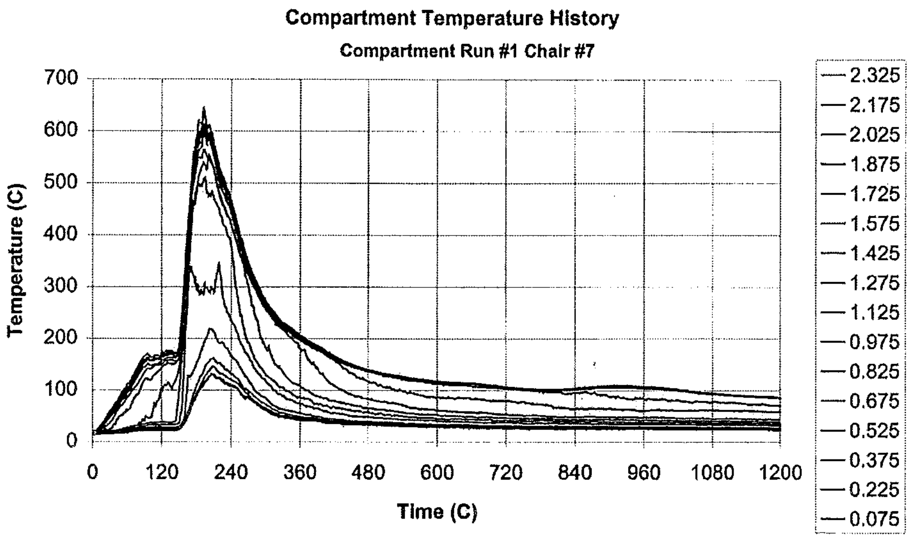
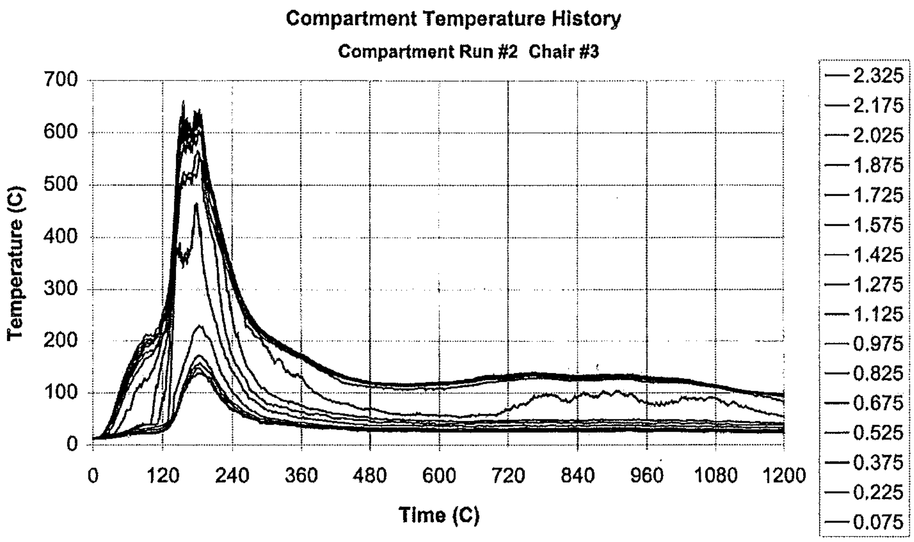


Figure 17 (Continued)



Compartment Temperature History
Compartment Run #1 Chair #7
Temperature (C)
Time (C)
700
600
500
400
300
200
100
0
0
120
240
360
480
600
720
840
960
1080
1200
2.325
2.175
2.025
1.875
1.725
1.575
1.425
1.275
1.125
0.975
0.825
0.675
0.525
0.375
0.225
0.075



Compartment Temperature History
Compartment Run #2 Chair #3
Temperature (C)
Time (C)
700
600
500
400
300
200
100
0
0
120
240
360
480
600
720
840
960
1080
1200
2.325
2.175
2.025
1.875
1.725
1.575
1.425
1.275
1.125
0.975
0.825
0.675
0.525
0.375
0.225
0.075

Figure: 17

4.2.4 Smoke Species

Analysers inside the exhaust duct measured the mole fractions of carbon monoxide, carbon dioxide and oxygen. Appendix B contains smoke species history curves.

Toxic Smoke Species

The greatest carbon monoxide mole fraction of 0.00579 was recorded for chair number 7 at 206.2 seconds from ignition. The lowest carbon monoxide mole fraction was recorded for chair number 16 at 151 seconds from ignition. The variation of carbon monoxide fraction was 0.00229. The greatest time for a chair to reach its maximum carbon monoxide concentration was from chair number 13 which took 220.4 seconds to reach a carbon monoxide mole fraction of 0.00365. The slowest time was from chair number 19 which took 145.8 seconds to reach a carbon monoxide mole fraction of 0.00478. The variation of the time was 74.6 seconds.

The greatest carbon dioxide mole fraction of 0.0362 was recorded for chair number 10 at 168.3 seconds from ignition, and the lowest carbon dioxide mole fraction of 0.247 for chair number 13 giving a variation of 0.0115. Chair number 16, took 147 seconds to reach a carbon dioxide mole fraction of 0.0259 giving a difference of 75.6 seconds from chair 13.

Oxygen Depletion

Oxygen depletion is one of the most important parameters of room condition, not only as an indication of tenability limits but also as a basis for calculating heat release-rate.

The greatest concentration of oxygen in the exhaust duct was of 0.1797 at 221.5 seconds from ignition for chair number 13. While the lowest concentrations of oxygen in the exhaust duct was for chair number 7 measuring 0.1689 at 207.3 seconds from ignition. This gave a variation in the oxygen mole fraction of 0.0108. Chair number 13 was the slowest chair to reach minimum oxygen mole fraction taking 221.5 seconds from ignition to reach mole fraction value of 0.1797 while chair number 19 was the fastest chair to reach its minimum oxygen mole fraction of 0.1739 at 150.3 seconds from ignition. The variation in time to reach minimum oxygen concentration was 71.2 seconds.

The Ratio between Carbon Monoxide and Carbon dioxide:

The ratio CO / CO2, (ratio of the mass of carbon monoxide to the mass of carbon dioxide produced by the oxidation of the foam as a fuel), is one of the most important parameters to define the combustion chemistry for each one of tested foams. The Ratio CO / CO2 history for the six chairs is presented in figure 18. The mole fraction histories for carbon monoxide and carbon dioxide as an expression of their concentration related to time were measured during the experiment. The oxygen depletion rate is also expressed in the mole fraction as a measurement of its concentration. However the first two runs were conducted without using a smoke curtain around the exhaust hood and less capture. The flow rate for these first two runs started at 3.6 kg/sec and maintained steady at 3.0 kg/sec where the other four runs, the use of curtain maintained the flow rate at 4.0 kg/sec. For that reason comparing only between the measured mole fractions might not be accurate, however comparing between chairs considering the ratio CO / CO, which was calculated from the mass fractions for both carbon monoxide and carbon dioxide give a better comparison between tested chairs.

Analysers in the exhaust duct measured the mole fraction for carbon monoxide (Xco) and carbon dioxide (Xco2), not the mass fraction of carbon monoxide (Yco) and carbon dioxide (Yco2). Mole fractions can be converted to mass fractions by multiplying the mole fractions with the ratio between the molecular mass of smoke species and the molecular mass of the fuel, ie.

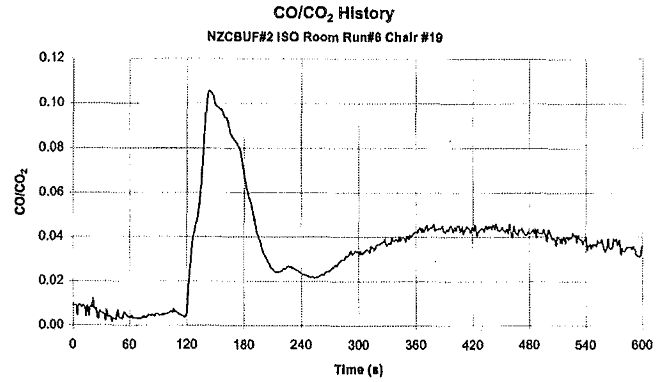
$Y_{co} = X_{co} (M_{co} / M_n)$ and $Y_{co2} = X_{co2} (M_{co2} / M_n)$

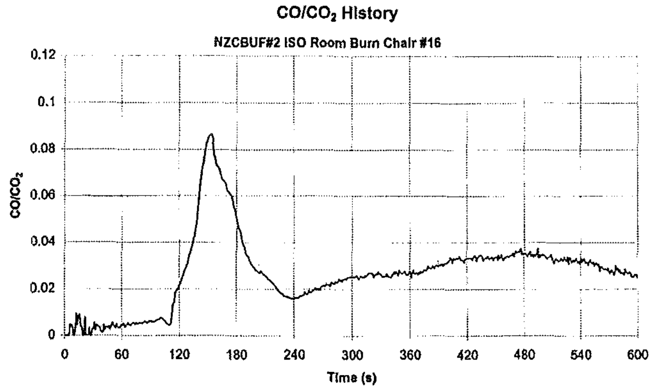
Therefore $CO / CO2 = Y_{co} / Y_{co2} = (X_{co} / X_{co2}) (M_{co} / M_{co2})$

$CO / CO2 = (X_{co} / X_{co2}) (28 / 44)$

Item	Max. CO / CO2	Time to max. (sec)	Estimated average CO / CO2
Item # 1 (Chair # 3)	0.0955	178.8	0.0527
Item # 2 (Chair # 7)	0.114	197.5	0.0461
Item # 3 (Chair # 10)	0.0876	161.7	0.0395
Item # 4 (Chair # 13)	0.0982	219.3	0.0329
Item # 5 (Chair # 16)	0.0896	152.6	0.0329
Item # 6 (Chair # 19)	0.1094	142.5	0.0329

Table 7: (CO / CO2) Ratio.





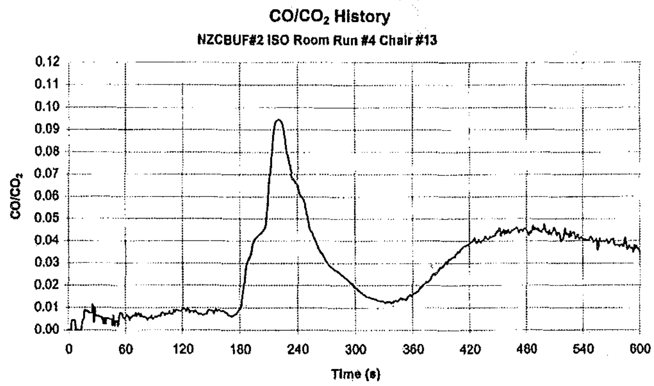


Figure 18: Smoke Species history (Continued)

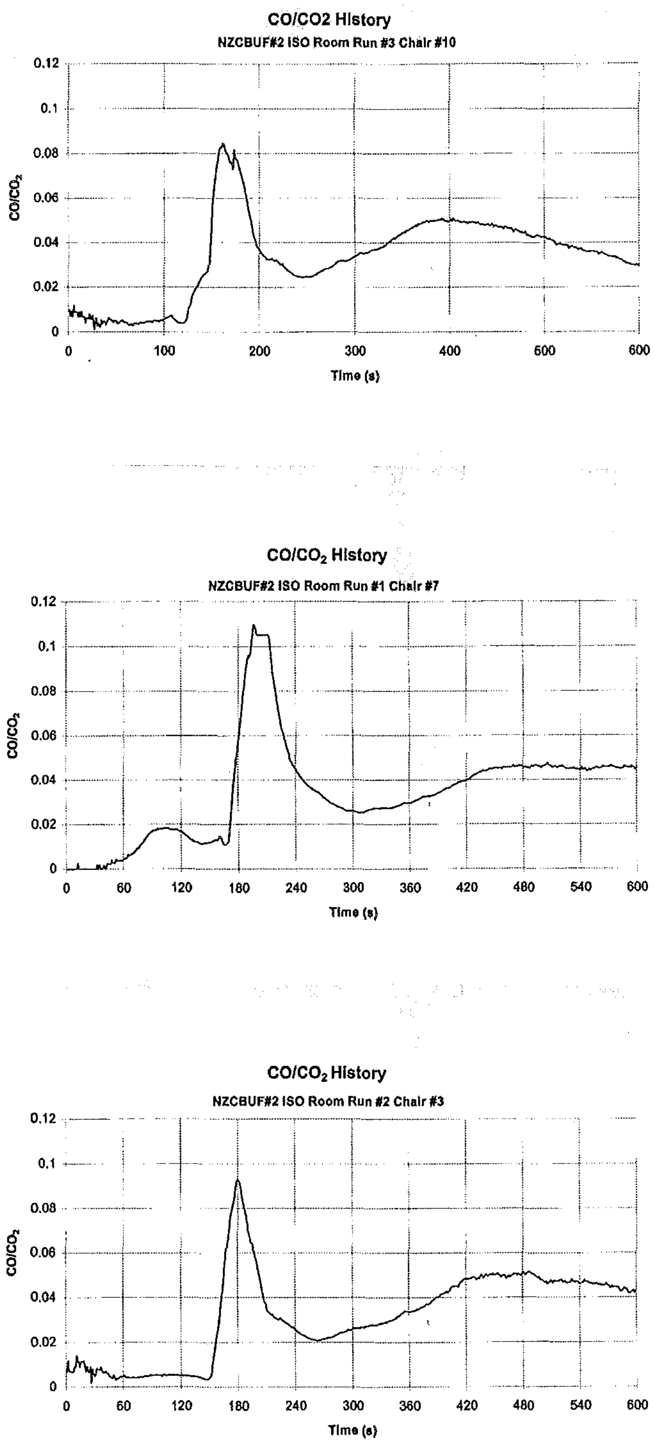

CO/CO2 History
NZCBUF#2 ISO Room Run #3 Chair #10
CO/CO₂
Time (s)
CO/CO$_2$ History
NZCBUF#2 ISO Room Run #1 Chair #7
CO/CO$_2$
Time (s)
CO/CO$_2$ History
NZCBUF#2 ISO Room Run #2 Chair #3
CO/CO$_2$
Time (s)

Figure: 18

4.2.5 Mass-Loss

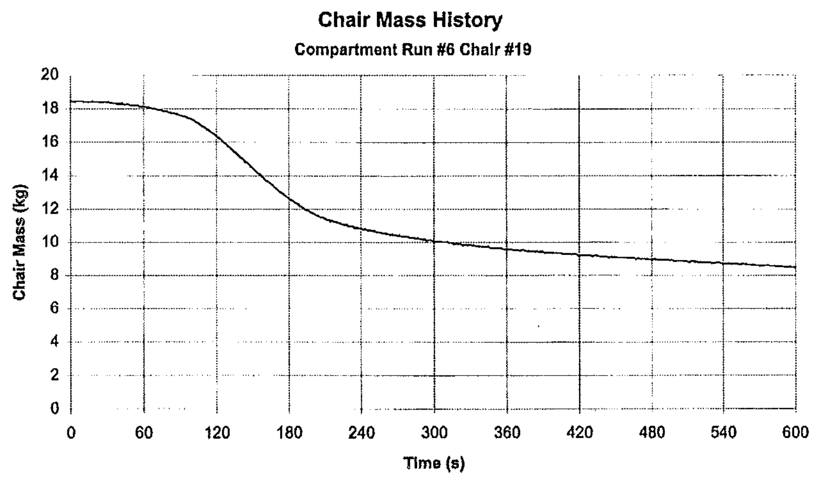
Mass loss rate ($\dot{m}$) has been used empirically to predict the burning rate when the heat of combustion for any fuel is known. In this empirical relationship the mass loss rate is proportional to the heat-release rate (energy release rate / burning rate). The slope of the mass history curve could give the mass-loss rate during full development of the fire; this could be calculated by dividing the time period of the full fire development over the change of mass during this period. The mass-loss rates for the tested chair are presented in table 8. The mass-loss history curves for the six chairs tested inside the ISO room are shown in Figure 19.

Item	Chair Number	Mass loss Rate (kg/sec)
Item # 1	Chair # 3	0.0636
Item # 2	Chair # 7	0.0496
Item # 3	Chair # 10	0.0500
Item # 4	Chair # 13	0.0417
Item # 5	Chair # 16	0.0417
Item # 6	Chair # 19	0.0500

Table 8: Mass-Loss Rate

Average value for heat of combustion (Δ Hc) for each type of tested foams could be obtained by using data from table number 8 (Mass-Loss Rate) and data from table number 3 (Heat-Release Rate).ie.

Heat Release Rate = (Δ Hc) m°



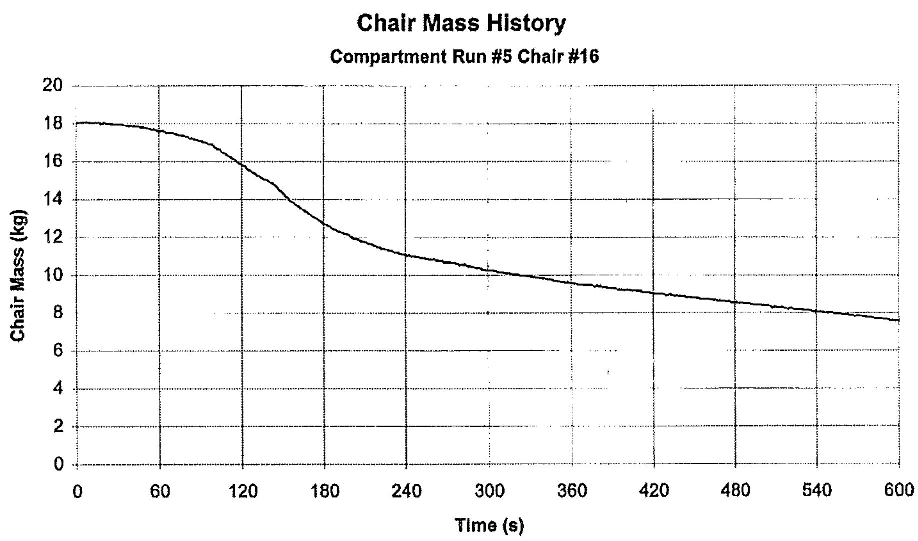
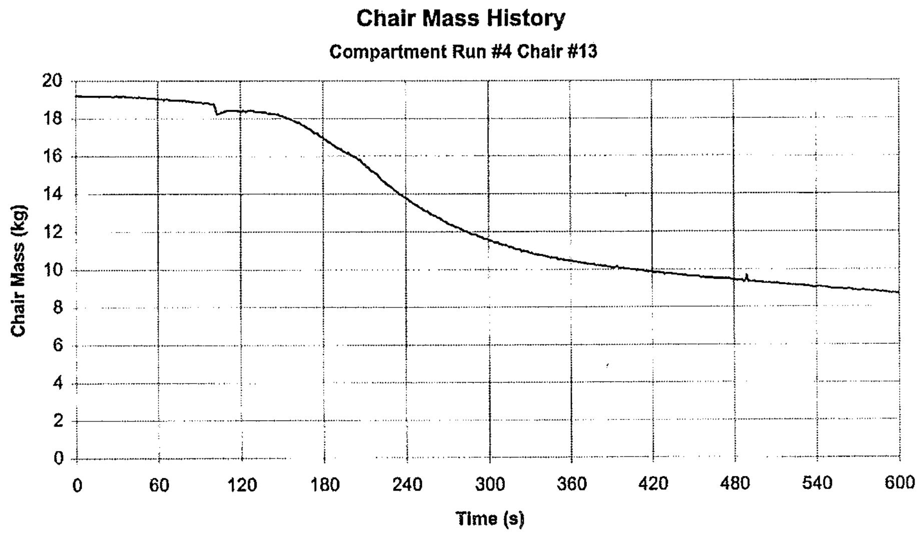


Figure 19: Mass-Loss History (Continued).



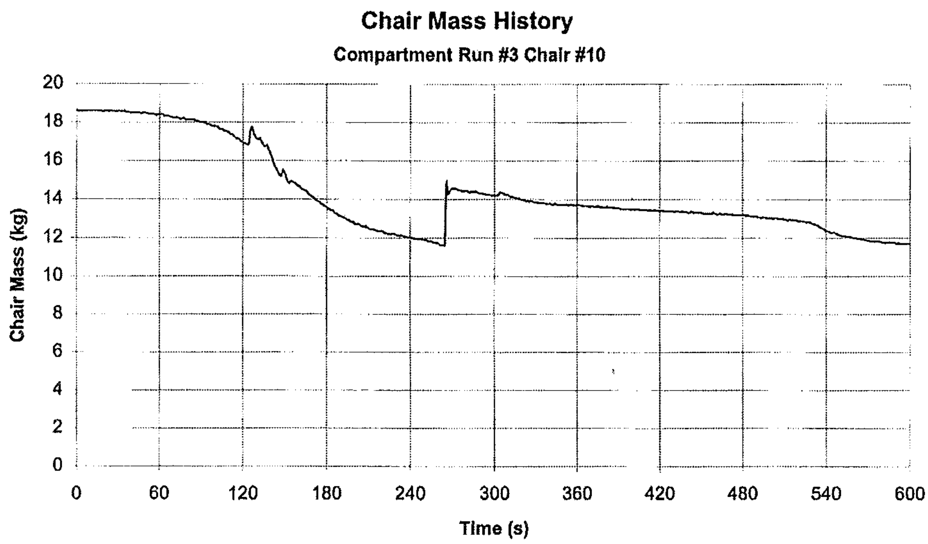
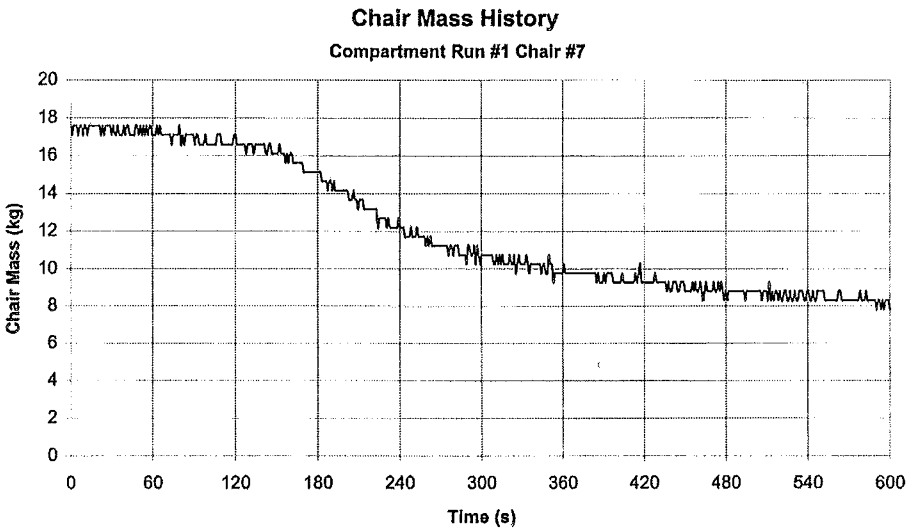


Figure: 19 (Continued)


Chair Mass History
Compartment Run #1 Chair #7
Chair Mass (kg)
20
18
16
14
12
10
8
6
4
2
0
0
60
120
180
240
300
360
420
480
540
600
Time (s)

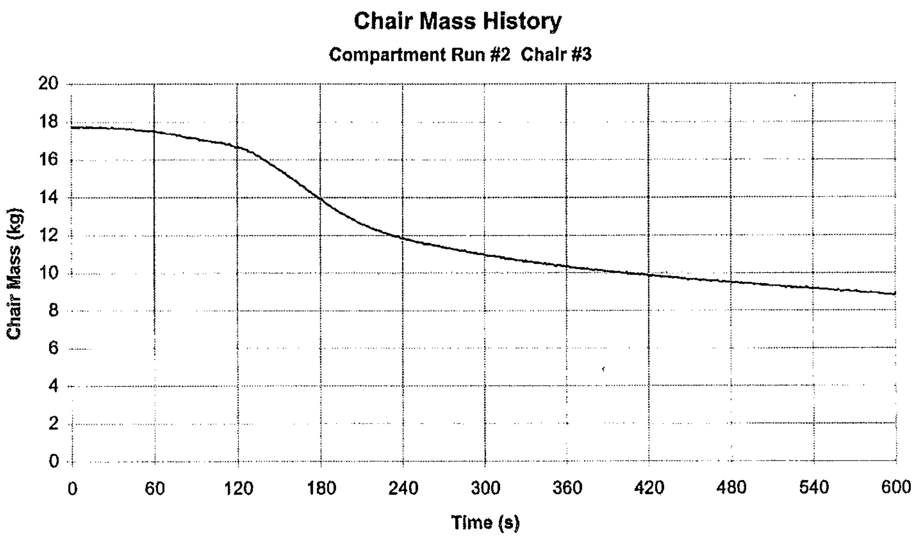

Chair Mass History
Compartment Run #2 Chair #3
Chair Mass (kg)
20
18
16
14
12
10
8
6
4
2
0
0
60
120
180
240
300
360
420
480
540
600
Time (s)

Figure: 19

4.2.6 Heat-Flux

The peak heat-flux was measured at the floor centre of the fire-test room from the six tested chairs is presented in Table 9.

Item	Chair Number	Peak Heat-Flux at Floor Level (kW/m^2)	Time (sec)	Time to 20 kW/m^2
Item # 1	3	36.74	169.0	144.0
Item # 2	7	----	----	----
Item # 3	10	41.60	155.1	124.5
Item # 4	13	39.64	212.6	192.0
Item # 5	16	34.30	140.4	101.5
Item # 6	19	47.75	163.6	110.0

Table 9: Heat-Flux

The heat-flux at the floor level has an order from the most hazardous chair to the better performance chair close to the order that was found in table number 3 (heat-release Rate). heat-flux value at the floor level depends mainly on the room ceiling height, which affects the radiation from accumulated layers of hot smoke. Time to reach 20 kW/m^2 heat-flux when the burning item starts one set of flashover and will ignite other items is presented in Table 9.

Chapter 5
Comparison between ISO and Furniture Calorimeter

Part of research recently carried out at the University of Canterbury used the Furniture Calorimeter test. A series of tests were conducted on a group of single upholstered chairs. Six chairs tested using the furniture calorimeter were selected from this group of chairs. The chairs were identical in all aspects to those in the ISO study, i.e. they had the same foam type and the fabric type as for the six chairs tested in the ISO room. Access to the data collected from the furniture calorimeter test for five chairs of the selected group allowed a comparative discussion of the difference in foam behaviour in the two sets of experiments. This comparison is a study of the impact of the surrounding environment on the foam behaviour, and seeks to answer the research question number 2. Do the foams tested in a compartment fire differ from those in a large space? The ISO Room as a controlled enclosed environment was expected to be more conservative regarding fire hazards compared to the more open space situation as used in the furniture calorimeter experiments. The comparison between these two sets of experiments is presented in table 10. (Note that: There was no counterpart for chair number 16.)

Item Number	F. C. Chair Number	ISO Chair Number	Chair Code
Item # 1	Chair # 2	Chair # 3	21-G-S2-1
Item # 2	Chair # 6	Chair # 7	21-H-S2-1
Item # 3	Chair # 9	Chair # 10	21-I-S2-1
Item # 4	Chair # 12	Chair # 13	21-J-S2-1
Item # 5	Chair # 15	Chair # 16	21-K-S2-1
Item # 6	Chair # 18	Chair # 19	21-L-S2

Table 10: Comparison Arrangement.

5.1 Heat-Release Rate

Two categories were considered in the comparison between foam behaviour inside the ISO Room and the Furniture Calorimeter. Firstly, the peak heat-release rate produced by each chair in both two sets of experiments which examine the fire size and which might affect the life safety and time to escape for individuals in other places of the building. Secondly, the time to reach a heat-release rate of 500 kW for each chair in both two sets of experiments which affects the time available for individuals inside the room of fire origin before the fire starts to grow rapidly and conditions become lethal.

Peak Heat-Release Rate

Data for peak heat-release rate and time to reach peak-heat release rate obtained from both the ISO Room test and the Furniture Calorimeter test for the identical items is presented in table 11. For all chairs, the peak heat- release rates measured inside the ISO room were higher than in the furniture calorimeter test. This is a result of re-radiation and feed back from the ISO room walls and ceiling into the fire. Generally chairs that produced a higher peak heat-release rate inside the ISO Room, also produced higher peak heat release rates in the furniture calorimeter relative to the other chairs. This was the same result for the chairs, which produced lower values of peak heat- release rates. However the sequence of the values is different when compared between any two particular chairs within each set of experiments, such as chair number 3 and chair number 7. It appears that some foam might have a better fire performance in a larger space than that in an enclosed smaller space. This means that the feedback from the room affected the performance of some foam, but not others. Further investigation might be needed to establish the reasons behind this difference, which goes beyond the scope of this study.

Item Number	ISO Room		Furniture Calorimeter	
	Peak HRR MW	Time (sec)	Peak HRR MW	Time (sec)
Item # 1	1.45	184.3	0.688	149.7
Item # 2	1.34	196.3	0.841	149.2
Item # 3	1.56	144.0	0.952	172.6
Item # 4	1.52	210.4	0.593	214.6
Item # 5	1.59	136.0	---	---
Item # 6	1.82	138.1	1.05	122.9

Table 11: Comparison of Peak Heat-Release Rate.

<u>Time to reach 500 kW Heat-Release Rate</u>

Table 12 presents time taken by each chair to reach 500 kW hear-release rate in both sets of experiments when the fire starts a very rapid growth.

Item	Time to reach 500 kW Inside ISO Room (sec)	Time to reach 500 kW Furniture Calorimeter (sec)
Item # 1 (Chair # 3)	130.0	131.0
Item # 2 (Chair # 7)	159.0	119.0
Item # 3 (Chair # 10)	104.5	102.0
Item # 4 (Chair # 13)	162.8	200.0
Item # 5 (Chair # 16)	96.5	✳
Item # 6 (Chair # 19)	102.7	105.5

✳ Item not tested in furniture calorimeter.

Table 12: comparison of time to reach 500 kW.

At early stages of fire, pre-flashover stages, the surrounding environment has no great effect on fire growth . The room walls and ceiling did not heat sufficiently yet to re-radiate heat flux and accelerate the fire growth.

5.2 Smoke Species

Toxic smoke species concentrations measured in the exhaust duct of both the ISO Room and the Furniture Calorimeter were in terms of mole fraction for carbon monoxide and carbon dioxide. The maximum mole fraction was measured for each chair during both experiments and time to reach this maximum value was used to calculate the mass fraction as a basis for the comparison to study the impact of the surrounding environment on the fire hazards. The minimum mole fraction measured in the exhaust duct during both experiments and time taken to reach this minimum value is also taken as a basis for comparison to study the impact of the surrounding environment on the oxygen depletion. The results obtained from both the ISO Room and the Furniture Calorimeter for mole fractions have the same order from the worst chair to the best chair. It was found that the greater maximum mole fraction recorded in the exhaust duct for carbon monoxide and carbon dioxide occurred from the same chair in both experiments, but there was a difference in scale. Also the lowest maximum-recorded values occurred from the same chair in both experiments. That was the same for the time to reach these highest and lowest values. The same observation was found for the oxygen depletion and time taken to reach minimum oxygen concentration in the exhaust duct.

Comparison between the Ratio CO / CO2

The flow rate of smoke was different in both sets of experiments, the ISO Room and the Furniture Calorimeter. Therefore comparison, presented in table 13, between the two sets of experiments used the measured values of carbon monoxide mole fractions and carbon dioxide mole fractions from the experiments to compare between the ratio CO / CO2 for mass fractions using the equations presented in section 4.2.4.

Item	Maximum CO / CO2 ISO Room	Maximum CO / CO2 Furniture Calorimeter
Item # 1	0.096	0.002
Item # 2	0.114	0.011
Item # 3	0.087	0.006
Item # 4	0.098	0.006
Item # 5	0.089	----
Item # 6	0.109	0.006

Table13: Comparison of the Ratio CO / CO2

From table 13 it is obvious that the surrounding environment has a great impact on the degree of toxicity produced by each chair by affecting the combustion chemistry.

Chapter 6
Discussion

This chapter discusses the key ideas that emerge from the results in particular those which seek to provide answers to the research questions, after starting by the limitation of the experiments.

6.1 Limitations

Firstly, the first two ISO Room experiments were carried out in the absence of a curtain around the exhaust duct. The flow rate for the first two runs maintained at 3.0 kg/sec while it maintained at 4.0 kg/sec for the last four runs. This means that the concentration value of the smoke sample recorded in the exhaust duct during these two first runs may have been affected so as to give an underestimate.

Secondly, the data presented in graphs and tables cannot be used to estimate the tenability limits of the combustion products because recorded species concentrations were in the exhaust duct and not the upper layer of the fire-test room.

The third limitation concerns the comparison between the two sets of experiments where an inexact number of items were compared. The ISO Room six chairs with six different foams and the Furniture Calorimeter with only five chairs is an incomplete comparison.

6.2 ISO Room

Chairs were tested inside the ISO room and the analysis of the results shows that the uses of different types of foam in upholstered furniture produces different types of fire hazards. Data recorded from the experiments for each chair were heat-release rate, heat-flux, temperature profile inside the fire-test room, temperature history inside the room, and the mole fractions of carbon monoxide, carbon dioxide and oxygen inside the exhaust duct and the mass loss rate. The values recorded for the heat-release rate from a single upholstered chair inside the ISO Room varied from 1.82 MW, produced by chair number 19 to 1.34 MW produced by chair number 7. And the room temperature values varied from 674 °C, occurring from chair number 10, to 643 °C, produced by chair number 7. On the other hand the smoke concentration inside the exhaust duct recorded from a single burning upholstered chair inside the ISO Room varied from 0.0362 carbon dioxide mole fraction, produced from chair number 10, to 0.0247 carbon dioxide mole fraction produced by chair number 13. It also varied from 0.00579 carbon monoxide mole fraction produced from chair number 7 to 0.00350 carbon monoxide mole fraction produced from chair number 16. The ratio CO / CO_2 varied from 0.114 to 0.087. The minimum oxygen mole fraction of 0.1689 occurred with chair number 7 compared to 0.1797 caused by chair number 13.

It was found that some of the chairs produced more than one type of fire hazard and some others relatively had a better performance than the others did.

Chair number 19 recorded the greatest peak heat-release rate (1.82 MW) it was also the fastest chair to reach its peak heat-release rate (138 sec) and was the second to reach 500 kW after chair number 16. The greatest maximum room temperature was recorded by chair number 19 (581 ° C, at 1 meter from the floor level, and 645 ° C at 1.8 metres from the floor). It also recorded greatest heat-flux at floor level (47.75 kW / m^2). At the same time chair number 19 was the second to record maximum carbon monoxide and carbon dioxide mole fraction, and also the second for time to reach these maximums.

Chair number 16 followed chair number 19 as the second chair to reach peak heat-release rate and maximum room temperatures, and also to produce the highest toxic species concentrations.

Chairs number 10 and 3 were not the first or the second for any fire hazards examined however both of them recorded relatively bad fire performance for all these hazards compared to the other chairs.

Chair number 13 had a better fire performance compared to the previous chairs while chair number 7 was the best of all the chairs tested.

It also found that the chairs built up from a foam having a fire retardant added had better behaviour than the others without fire retardant added.

6.3 Furniture Calorimeter

This section discusses findings related to the second research question. The surrounding environment was found to have a significant impact on the foam behaviour and the degree of fire hazard produced. The concentrations of toxic gases were lower in a large space than in a small compartment. However two factors to be considered for the surrounding space are the compartment area and the ceiling height. The compartment area might increase or decrease the time taken for the horizontal movement of the smoke, which took place at relatively late stages of the fire. Ceiling height was a more critical factor than compartment area in that the lower ceiling in the ISO experiments led to more rapid smoke accumulation and heat feedback from the ceiling. For chair number 19 the peak heat-release rate of 1.82 MW was recorded inside the ISO room compared to 1.05 MW which was recorded in the Furniture Calorimeter test. These results were similar to the other chairs in both two sets of experiments for the heat-release rates results pattern. The carbon dioxide mole fraction of 0.0293 in the exhaust duct produced by chair number 19 inside the ISO compared by 0.0163 produced by the same chair in the furniture calorimeter test. And carbon monoxide mole fraction of 0.00478 in the exhaust duct produced by chair number 19 inside the ISO compared by 0.000159 produced by the same chair in the furniture calorimeter. The Ratio CO / CO2 for chair number 19 was 0.096 during the ISO Room compared to 0.002 during the Furniture Calorimeter test. These results were similar to the other chairs in both two sets of experiments for carbon dioxide and carbon monoxide mole fractions, also for the ratio CO / CO2. The minimum oxygen mole fraction in the exhaust duct recorded for chair number 19 in the ISO was 0.1739 compared to the minimum mole fraction of 0.1889 for the same chair in the furniture calorimeter test. These results were similar for the other chairs in both two sets of experiments for the oxygen depletion results pattern.

Comparison between heat-release rates in both sets of experiment, the ISO Room and the Furniture Calorimeter, shows that there were differences between the order of the chairs from the worst to the best, regarding the measured heat-release rates. These differences were not great numerically, however they show that the material property of the different foam types might have a role in the foam behaviour in the fire, where the conditions of both experiments in the ISO Room and the Furniture Calorimeter were consistent for all runs.

Both experiments followed the prescribed procedure correctly. However the numerical difference of the gas samples in the exhaust duct between both experiments is considered relatively big, which highlights the impact of the surrounding environment on the burning behaviour of the tested foams. This is mainly the ceiling height, which has a significant effect on the heat- release rate, which has a corresponding effect on the degree of toxicity and time taken to reach maximum concentration of toxic products.

Chapter 7
Conclusions

A set of six full-scale experiments was conducted successfully inside the university laboratory testing a New Zealand style of single upholstered chair. The six chairs tested had different foam types, but the same fabric, size, style, and construction. For all chairs the fire-test room reached untenable limits approximately one minute after ignition. From the experiments it was found that each type of foam presented different degrees of fire hazards and more than one fire hazard at the same time. But each of them had a rapid-fire growth. Foam coded (L) was the worst performance followed by foams coded (K), (I), (G) in the order of performance, whereas foams coded (J), (H) which had fire retardant added presented better performance.

This project goes part way to providing answers to the research questions stated in the introduction. It is clear from this study that one foam is more hazardous than the others are. The experimental results provided numerical values for the variations between the different tested foams in each one of the examined fire hazards. Therefore answers have been reached for the first question: Is one Polyurethane foam any less hazardous than another during the fire, and to what extent?. However this study raises questions concerning material composition and density of the foams and the effect of these on fire performance. An examination of the difference in composition and density of the foam was beyond the scope of this study.

It is clear from the comparison between both the ISO Room experiments and the Furniture Calorimeter tests that the larger space produced less hazardous effects than the smaller compartment. The foam performance in the large space (Furniture Calorimeter) was better than its performance inside the small room. This answer was reached concerning the second question: Do the foams tested in a compartment fire differ from those in a large space? However, this study, also raises many unanswered questions about the impact of the surrounding environment on the fire performance of the foams. Why for example were there differences in the order of worst to best chairs in the heat-release rate produced, and what factors have caused these differences. Clearly the ceiling height and room area are significant factors as an obvious difference between the two sets of experiments, however further research is needed in this area to examine other possible factors.

Chapter 8
Recommendations

Some foam types produced a greater peak heat-release rate, heat-flux, and peak temperature, on the other hand, some other foam types produced greater mole fractions of toxic smoke (concentration) and more rapid oxygen depletion, which was expressed in a minimum oxygen mole fraction. Some of the chairs produced more than one type of fire hazard at the same time and some of them had a relatively better behaviour than other chairs. However a comparison between chairs using different types of foam is just part of the comparison process where the other components of upholstered furniture may also exert an influence on the fire performance fabric, interliner, frame, and style design. Therefore the results obtained from the full-scale experiments and this report should be used together with other research concerning the other components of upholstered furniture.

Further research is needed to closely study the reasons behind the different behaviour of the tested foams related to chemical characteristics and material property of each type of foam. Also research is needed to test the effect of fire retardant adding on foam behaviour.

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Appendix A: Tenability limits

The effects on an individual when exposed to the highly toxic gases Carbon Monoxide.

CO% Concentration	**CO Part per Million**	**Exposure Time**	**Effects**
0.02	200	2-3 hours	Mild headache
0.08	800	45 minutes 2 hours	Mild headache Possible death
0.32	3,200	10-15 minutes 30 minutes	Dizziness Death
0.69	6,900	1-2 minutes 10-15 minutes	Dizziness Death
1.28	12,800	2-3 breaths 1-3 minutes	Unconscious Death

Table (1A) Effects of Carbon Monoxide Exposure [17]

The effects on an individual when exposed to the highly toxic gases Carbon Dioxide.

CO2% Concentration	CO2 Part per Million	Effects
0.5	5,000	Increased depth of breathing
3.0	30,000	Breathing rate Doubles
5.0	50,000	300% increase in breathing rate
10.0	100,000	Possible Death

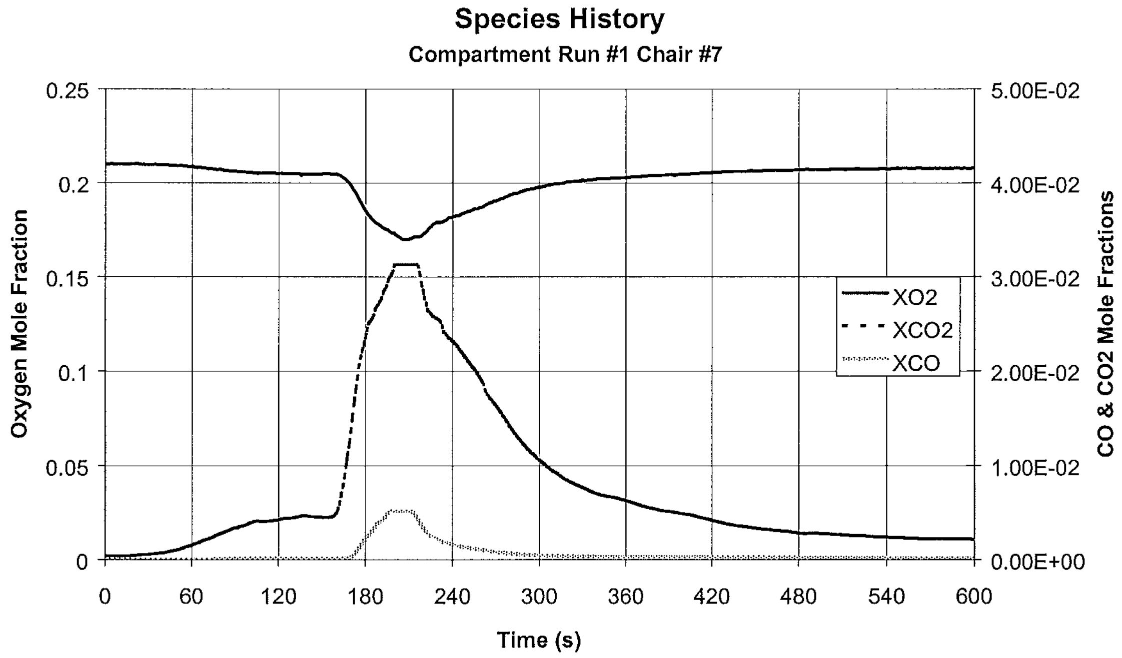
Table (2A) Effects of Carbon Dioxide Exposure [17]

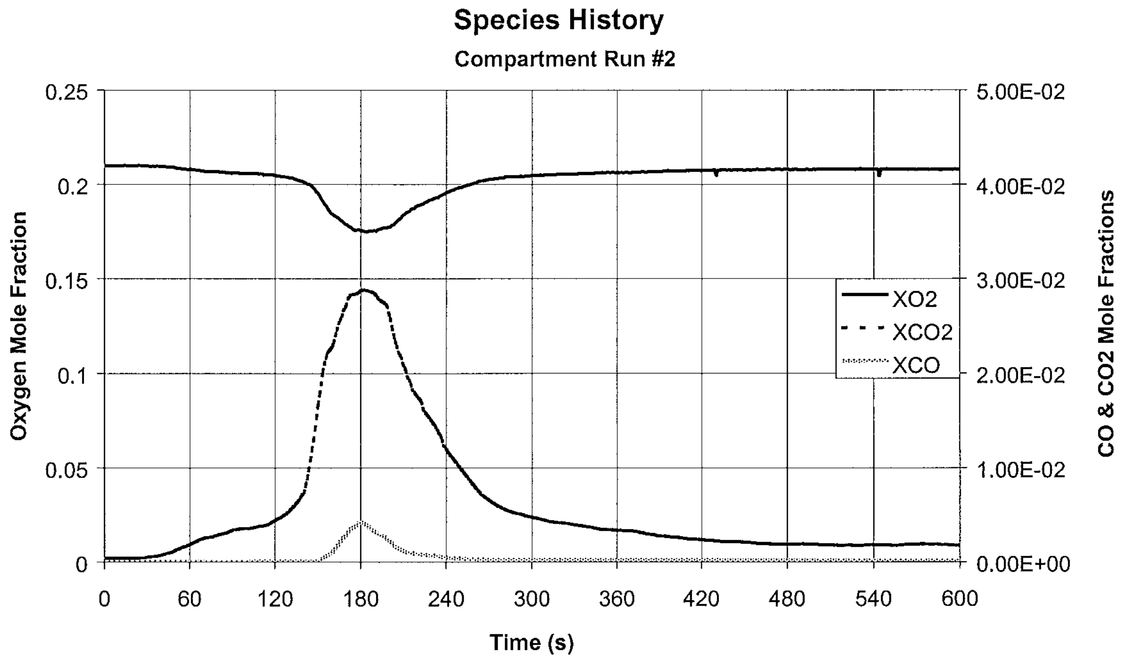
The effects on an individual when expose to Oxygen Depletion.

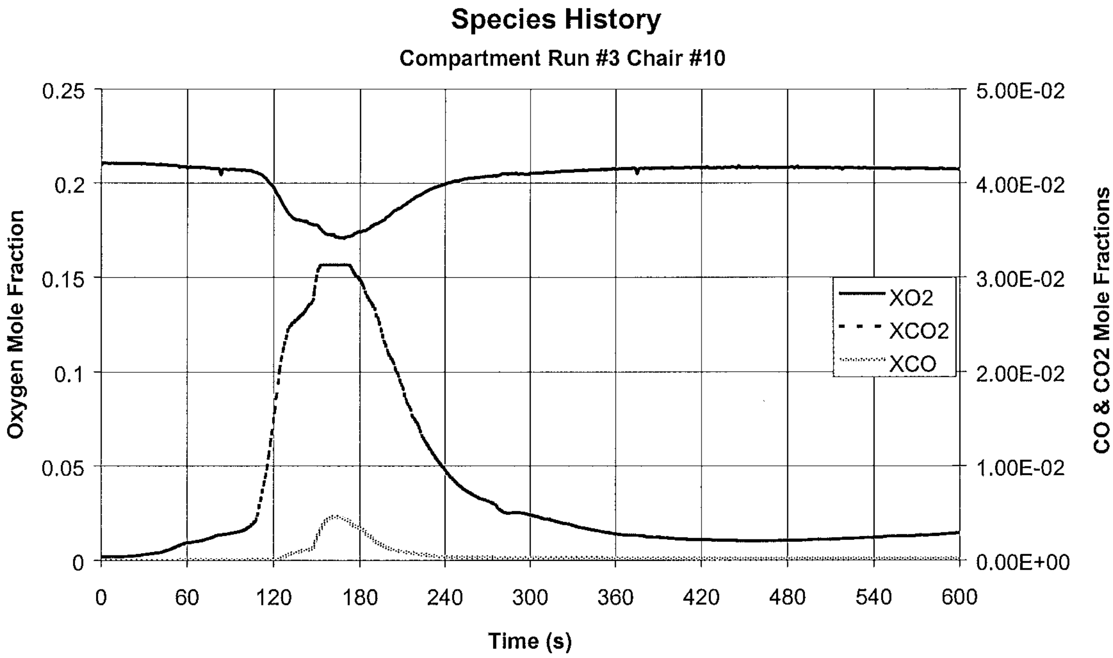
O2% Concentration	Exposure Time	Effects
21-17	Indefinite	Respiration volume decreases, loss of co-ordination and difficulty in thinking
17-14	2 hours	Rapid pulse and dizziness
14-11	30 minutes	Nausea, vomiting and paralysis
9	5 minutes	Unconsciousness
6	1-2 minute	Death within a few minutes

Table (3A): Effects of Oxygen Depletion

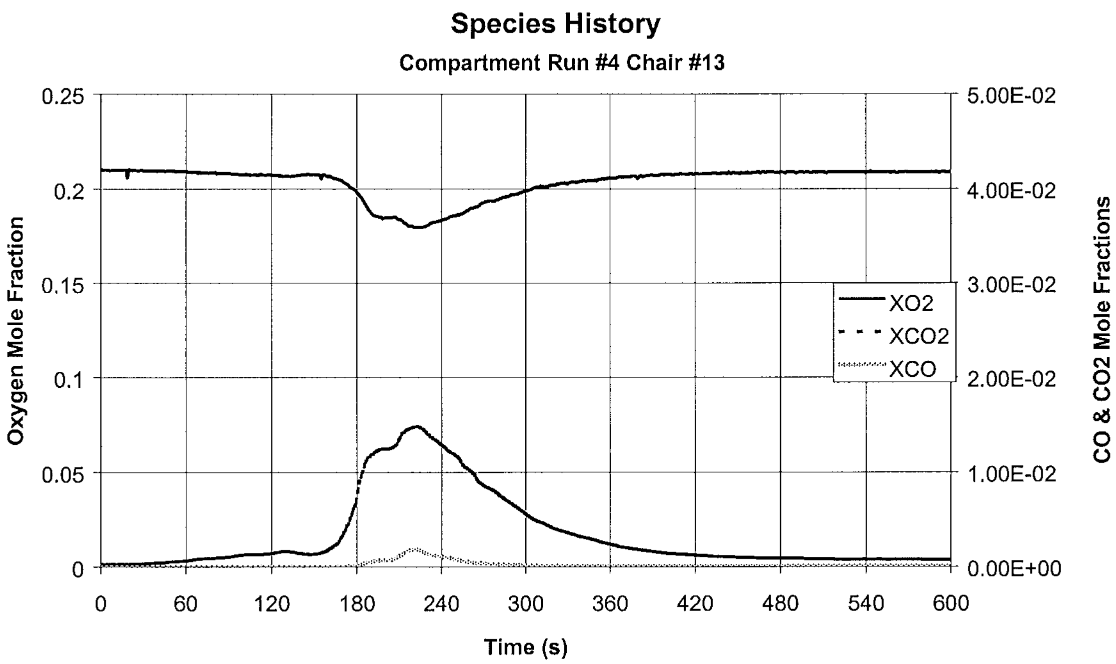
Appendix B; ISO Smoke Species History



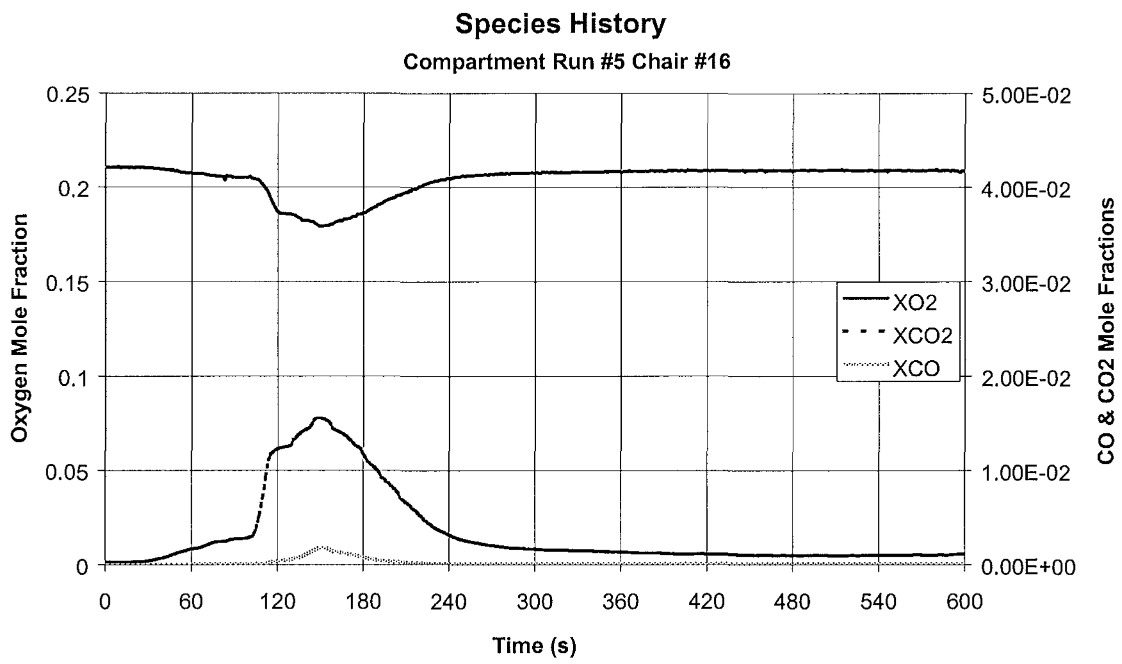




Species History
Compartment Run #3 Chair #10
0.25
0.2
0.15
0.1
0.05
0
Oxygen Mole Fraction
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
CO & CO2 Mole Fractions
XO2
XCO2
XCO
0
60
120
180
240
300
360
420
480
540
600
Time (s)



Species History
Compartment Run #4 Chair #13
0.25
0.2
0.15
0.1
0.05
0
Oxygen Mole Fraction
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
CO & CO2 Mole Fractions
XO2
XCO2
XCO
0
60
120
180
240
300
360
420
480
540
600
Time (s)



Species History
Compartment Run #5 Chair #16
Oxygen Mole Fraction
CO & CO2 Mole Fractions
0.25
0.2
0.15
0.1
0.05
0
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
60
120
180
240
300
360
420
480
540
600
Time (s)
XO2
XCO2
XCO

Carbon Monoxide Mole Fraction

Item	Peak X Co (E-2)	Time to peak X Co (sec)
Item 1 (chair # 3)	0.418	181.0
Item 2 (chair # 7)	0.679	206.2
Item 3 (chair # 10)	0.472	162.8
Item 4 (chair # 13)	0.365	220.4
Item 5 (chair #16)	0.350	151.5
Item 6 (chair #19)	0.478	145.8

Carbon Dioxide Mole Fraction

Item	Peak Xco (E-2)	Time to peak Xco2 (sec)
Item 1 (chair # 3)	2.88	181.0
Item 2 (chair # 7)	3.35	209.5
Item 3 (chair # 10)	3.62	168.3
Item 4 (chair # 13)	2.47	222.6
Item 5 (chair #16)	2.59	147.0
Item 6 (chair #19)	2.93	148.1

Oxygen Depletion

Item	Min Xo2	Time to Min Xo2 (sec)
Item 1 (chair # 3)	0.1747	184.3
Item 2 (chair # 7)	0.1689	207.3
Item 3 (chair # 10)	0.1707	168.3
Item 4 (chair # 13)	0.1797	221.5
Item 5 (chair #16)	0.1781	151.5
Item 6 (chair #19)	0.1739	150.3